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4TH BIENNIAL RESIDENTIAL BUILDING DESIGN & CONSTRUCTION CONFERENCE PROCEEDINGS

FEBRUARY 28—MARCH 1, 2018

THE PENN STATER CONFERENCE CENTER & HOTEL

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THE PENN STATER CONFERENCE CENTER & HOTEL

State College, PA USA

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PREFACE

Energy efficiency, indoor quality control, sustainability, resiliency, and natural hazard and disaster mitigation have been some of the main drivers for many innovations in residential building materials and architectural, structural, mechanical, and electrical systems in recent years. This past year, in particular, many homes were damaged to totally destroyed in wild fires or hurricane winds, storm surges and floods, which further underlines the need for re-thinking of how residential buildings should be designed and constructed in regions vulnerable to such hazards. There is also increasing demand for high performance, healthy, and affordable construction, and in particular, those that employ renewable energy sources. These and other relevant issues have encouraged government, foundations, philanthropic organizations, investors, researchers, design professionals, product manufacturers, developers, and other stakeholders to support or seek advancements in the state-of-the-art and state of-the-practice in the field of residential construction. Significant efforts are being expended to develop new materials, products, processes, procedures, and guidelines to improve the state of existing residential buildings and to incorporate innovations in design and construction of new buildings as well as retrofit projects. Because of the need for timely knowledge sharing and dissemination of the results of extensive R&D activities and new advancements and developments in the field, the Pennsylvania Housing Research Center (PHRC) at The Pennsylvania State University is pleased to continue organizing the Residential Building Design and Construction Conference series to serve the housing and residential construction industry for this purpose.

The 4th Residential Building Design and Construction Conference was held on February 28—March 1, 2018 at The Penn Stater Conference Center and Hotel in State College, Pennsylvania. The RBDC Conference series is intended to provide a forum for researchers, design professionals, manufacturers, builders, and code officials to exchange knowledge and understanding on the latest research and development advancements and to discuss and share their own findings, innovations, and projects related to residential buildings. The RBDC Conference includes papers and presentations on various issues related to residential buildings, which encompass single- and multi-family dwellings, mid-rise and high-rise structures, factory-built housing, dormitories, and hotels/motels.

The conference series intends to provide opportunities for contributors from academia, architectural, engineering, and construction (AEC) firms, builders, developers, product and system manufacturers, and government and code officials to submit papers and/or make presentations on most aspects of residential buildings including the following areas and topics:

- Aging-in-Place and Senior Living Housing
- Alternative /Renewable Energy Generating Systems
- Building Information Modeling (BIM) Application in Residential Construction
- Building Integrated Photovoltaic Systems
- Building Performance Assessment/Metrics/Verification Methods and Occupant Behavior
- Building Science and Building Enclosures
- Energy Efficient Building Components
- Fire Damage and Protection
- High Performance Residential Buildings
- Indoor Air Quality
- Innovations in Green Roofs and Façade/Envelope Systems
- Innovations in Residential Architecture and Design
- Innovations in Modular and Manufactured Housing
- Innovative and Emerging Housing Construction Methods/Systems
- Innovative Wall, Floor, Roof, Window, and Siding Systems
- Learning from the Performance of Residential Buildings under Natural Disasters
- Low-Income and Affordable Housing
- Panelized Building Components

- Resilient New Design and Retrofit of Existing Buildings under Natural Disasters
- Retrofit of Existing Buildings for Energy Efficiency
- Rural and American Indian Housing
- Serviceability and Life Safety Damage Aspects
- Smart Home Technologies
- Sustainable Housing Construction Materials and Methods
- Temporary Housing for Disaster Situations
- Whole Building Design Approach
- Zero-Net Energy Homes and Passive House Design

The presentations at the 4th Residential Building Design and Construction Conference have covered many of the above topics, including the following: aging-in-place, building enclosure performance, building information modeling, building science education, cross laminated timber construction, disaster resiliency, energy codes, fire resistant design, healthy homes, hurricane resistant coastal homes, innovative materials and systems, moisture management, net-zero energy, passive house, public housing, roofing, smart homes and cities, solar energy, sustainability, temporary housing, and tiny homes.

Two keynote speakers were invited for the conference: Professor Dr.-Ing. Bohamil Kasal, Director of the Fraunhofer Institute for Wood Research, Fraunhofer Wilhelm-Klauditz-Institut, Germany, and Professor Ryan E. Smith, Associate Dean of Research + Community Engagement and Director, Integrated Technology in Architecture Center (ITAC), University of Utah, College of Architecture + Planning. Professor Kasal discussed the German experience of home building through his presentation titled *"German Residential Construction -- What Can We Learn from It?"* Professor Smith presented new developments in offsite aspects of home building in his presentation titled *"Global Innovations in Residential Building: Prefabrication, Modularization and Automation."* The conference brought together university professors, researchers, graduate students, architects, consulting engineers, product manufacturers, and product related associations/councils who shared research/study findings or new developments in the field that offered insight into emerging trends and technologies, and provided better understanding of the current issues and challenges facing the residential construction sector.

The conference included one plenary session on each day of the conference that featured a keynote lecture, four parallel tracks that accommodated presentations in 24 sessions, which grouped presentations in the following general topic areas: Building Enclosures, Building Information Modeling, Building Science Education, Community Impacts, Cross Laminated Timber, Design Considerations for Development, Design Consideration for Policy & Social Components, Design Consideration for Senior Housing, Design of Small Homes, Energy & Resiliency Modeling, Design for Resiliency, High Performance Homes, HVAC, Materials, and Passive House. Three of the sessions were Special Sections that included presentations and panel discussion on the following topics: Cross Laminated Timber, Building Science Education, and UN Global Building Network (for energy efficient buildings). On February 27, the day before the official start of the conference, tours were offered for attendees to visit Building Components and Envelopes Research Lab in the Architectural Engineering Department, and 3D Printing Lab in Civil and Environmental Engineering Department where concrete is printed using a robot arm. On the evening of that day, a Research and Education Reception was also held for the conference attendees as the ice breaker where several graduate students presented their research posters.

We wish to thank the members of the Steering Committee and the Scientific Committee of the conference for their contributions. The support of the PHRC staff for logistics is gratefully acknowledged.

Proceedings Editors:
Ali M. Memari and Sarah Klinetob Lowe
March 2018

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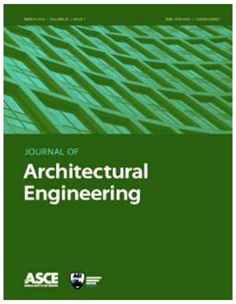

The American Society of Civil Engineers' (ASCE) Journal of Architectural Engineering (JAE) is running a Special Collection on Housing and Residential Building Construction. This peer-reviewed Special Collection covers various aspects of residential buildings, such as single- and multi-family dwellings, mid-rise and high-rise apartment buildings, dormitories, and hotels/motels, and includes technical research and development, technology transfer, case studies, and state-of-the-art review types of papers. See published papers here, *https://ascelibrary.org/page/jaeied/specialcollectionhousingandresidentialbuildingconstruction*.

Consider submitting a paper to the Special Collection. To submit a paper, go to the following site: *http://www.editorialmanager.com/jrnaeeng/*. When you see the "Additional Information" section, in response to the following question: "Is this manuscript part of a Special Issue? If yes, please provide Special Issue title and guest editor name.", please type the following in the dialogue box: "Housing and Residential Building Construction; Ali Memari".

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PENNSYLVANIA HOUSING RESEARCH CENTER

The Pennsylvania Housing Research Center (PHRC) serves the home building industry and the residents of Pennsylvania by improving the quality and affordability of housing. We conduct applied research, foster the development and commercialization of innovative technologies, and transfer appropriate technologies to the housing community. The PHRC is housed within the Department of Civil & Environmental Engineering at Penn State. For more information about the PHRC, check out our website, *phrc.psu.edu.*

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The Big Picture on Tiny Houses

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ABSTRACT

In August, 1970, the newly formed United States Council on Environmental Quality (CEQ) published *"Environmental Quality, The First Annual Report of the Council on Environmental Quality together with the President's Message to Congress (EQ1)"* While the CEQ estimated in 1970 that 9 trillion kWh's would be produced annually by 2000 (CEQ), real-world figures put global electricity production at 14.6 trillion kWh's, with a staggering 23.3 trillion kWh's electricity produced in 2013(EIA).

A small, but notable trend that may offset energy consumption is emerging in a grassroots architectural counterculture movement focused on designing and building tiny houses. These small dwellings, ranging between 120 square feet and 400 square feet, have a dual mission. They simultaneously aim to consolidate, simplify, and minimize the energy requirements of the average size house while relieving its occupants of the burdens that come with owning a typical house. Tiny houses are entering the mainstream, with half a dozen reality television programs airing on cable networks, many municipalities adapting local codes to allow for 'accessory' dwelling units and some banking institutions developing interest in tiny house lending models.

This paper will examine the driving forces behind the tiny house movement and question how that movement might evolve and adapt to accommodate future scenarios. A full-scale design / build prototype developed at Norwich University serves as a case-study that may help prove, disprove and bring into question the effectiveness of the tiny house.

WHAT WE KNEW, WHEN WE KNEW IT

1970 was a key year for environmental understanding in the United States. The National Environmental Policy Act (NEPA) and the Council on Environmental Quality (CEQ) were founded, and the first Earth Day was celebrated on April 22, 1970. The first annual report by the CEQ was published by the CEQ and legislation to create the Environmental Quality Improvement Act was passed that same year.

In the opening passages of *Environmental Quality, The First Annual Report of the Council on Environmental Quality together with the President's Message to Congress (EQ1),* then President Richard M. Nixon addressed congress by suggesting that the forthcoming document would be precedent setting in that it marked…

"…the first time in the history of nations that a people has paused,

> *consciously and systematically, to take comprehensive stock of the quality of its surroundings."* (CEQ_Nixon)

Nixon's preamble to the report continues like a calculated and sobering call to action and a just-in-time chance to remedy an unanticipated, potentially catastrophic situation.

This first report from 1970 immediately followed the formation of the NEPA as well as the CEQ, the latter of which acts as an executive office of the President of the United States. The first CEQ report presented current environmental data, including global population statistics, carbon dioxide (CO_2) levels in the atmosphere, pollution statistics for marine, air, and land, as well as current water usage estimates, among many other important data sets. The report also presented projections of many of these data sets for the years 2000 and 2010 respectively and theorized consequences associated with these projections. Like the opening salvo by President Nixon, the tone of the report is both grave and optimistic. The report has an entire chapter devoted to the potential for humanity to unintentionally alter global climate patterns. While global warming due to the greenhouse effect caused by CO_2 was theorized and observed in the eighteen hundreds, the first annual report of the CEQ is significant because it unquestionably marks a turning point in a nation's collective awareness of the severity and challenges of maintaining balance in our environment. And while the first annual report of the CEQ may not have developed ground-breaking science on climate change, it may very well be the first report of its kind to make the existing science of the day available to a mainstream audience. In one sense, the report may be seen historically as nothing short of a *declaration of environmental accountability.*

The tenth annual report, issued under the Carter administration in 1979, is an exhaustive 816-page report that, like the Nixon administration's report, takes a firm position on the direction of energy conservation, our collective responsibilities as stewards and what changes could be made to prevent ecological ruin. Most importantly, the tenth CEQ report clearly identifies what being *effective* means in terms of environmental stewardship. The report states the facts, but offers a clear analysis, and ultimately a clear ideology and position regarding the gravity of those facts. For example, when reporting on the rise of CO_2 in the atmosphere, the report quotes Dr. George Woodwell stating,

> *"If we wait until there is absolute proof that the increase in CO_2 is causing a warming of the Earth it will be twenty years too late to do anything about it."* (CEQ_Carter)

The CEQ continued to publish annual reports until 1995, when congress passed the Federal Reports Elimination and Sunset Act (Public Law 104-66), which focused on reducing paperwork in the federal government. During its 25 years of publication, the CEQ Annual Reports took a curious up-and-down trajectory regarding concern for mankind's influence on the environment and how data and science got presented. More curious however is how the data and science was interpreted and related to the reader. Where the first and tenth reports conveyed a sense of urgency, later reports are less committed to this sense of urgency and may even leave the reader questioning the underlying reason for the existence of the reports.

Where the tenth CEQ report follows in the footsteps of the first report by offering facts, overtly clear positions on those facts, and steps to make those positions effective, the final report issued in 1997 under the Clinton administration is a remarkably different document. About half the size of the tenth CEQ report under the Carter administration, it focuses on the advent of the Internet and how access to information will influence our shared responsibility for the environment. In step with the focus on how connectivity and the availability of information will effect the environment, part two, chapter five on *Air Quality* mentions progress and reductions made in lead, carbon monoxide, methane, and many other hazardous particulates in the atmosphere, but offers no panoramic view of what these reductions mean to our environment. Curiously, there is no mention of CO_2. Only in part two, chapter nine, titled *Energy*, is there mention of the record high levels of CO_2 in the atmosphere. And although mention is made of the connection between greenhouse gas (CO_2) and climbing global mean temperature, any overt mention of anxiety for this is absent. To further confuse things, table 11.6 in the appendix (CEQ_Clinton), which is credited to noted climate scientist James Hansen while he was with the Goddard Institute for Space Studies, indicates that *Annual Average Global Temperature* (AAGT) only rose 0.78˚F from 1866 to 1997. When seen within the relative annual fluctuation of 1.51˚F for average highs between this time period, 0.78˚F seems like a relatively low figure, and possibly within the normal fluctuation. Only in the context of other information in the table however can one glean that *AAGT* was in fact on a steady rise in 1979. So, rather than providing a deliberate scientific position and recommendation on environmental quality and steps for improvement, the final report of the CEQ instead provides an excellent host of energy usage facts and web links. The facts are there, but the reader is left to deduce the significance of the facts. The environment, something everyone, regardless of political party, could get behind seems to have become politicized, and energy availability became the focus rather than the consequences of over consumption. In a sophisticated, possibly covert way, the final annual report by the CEQ may be cleverly telling the truth but misleading its readers. In the context of the earlier mentioned chapter on *Air Quality* one might be led to believe that the environment was on a solid trajectory of healing. In the context of previous reports, the final CEQ report may be the most sophisticated publicly-issued document of green-washing.

It's remarkable that although the CEQ still exists, it has been largely removed from the public. Not only does it no longer issue a publicly available annual environmental report, on January 20, 2017 with the inauguration of President Donald J. Trump, the CEQ's website was removed from the Whitehouse.gov website. While mention of the CEQ is still present on the website as a single-page information section telling about the role of the CEQ, one cannot glean any relevant environmental information. In fact, as of January 20, 2017 the Whitehouse.gov website removed any mention of environmental sustainability. While mention of conserving the environment is referred to in the *America First Energy Plan* on the current administrations Whitehouse.gov website, and includes a sentence regarding our collective need to *'protect our clean air, and clean water',* it's difficult to tell the sincerity of this mention when it's preceded by paragraph after paragraph declaring the need for a more secure, domestic-based energy future. In the context of the current administration, concern for the environment is focused on securing use of natural resources, not the effects of the use of those resources. Remarkably, the former Obama Administration CEQ website is still publicly available through the Obama Administration Whitehouse archives (CEQ Obama).

Currently, with authorization from congress, scientists from thirteen independent federal agencies publish a National Climate Assessment (NCA) every four years. The most recent of these documents, officially titled *U.S. Global Change Research Program Climate Science Special Report* (CSSR), was leaked to the press in early August 2017, and published by the New York Times on August 7, 2017. The report, which specifically indicates mankind as being responsible for the rise in average temperatures across the United States and is currently under review by the Trump Administration, states;

> *"It is extremely likely that more than half of the global mean temperature increase since 1951 was caused by human influence on climate (high confidence)."*

VIRTUE, IGNORANCE, and REGRET

In *Book III* of *Nicomachean Ethics* Aristotle works to define what is virtue by distinguishing between involuntary action and voluntary action. He postulates that involuntary action is the result of either compulsion or ignorance, and further defines ignorance as *involuntary ignorance* and *non-voluntary ignorance.* To begin with, he establishes that an action taken in ignorance must result in remorse or regret. This distinction is further refined by the difference between actions that cause distress followed by regret, and actions that cause distress but are not followed by regret. Meaning, when we act in ignorance and cause distress without regretting that distress, we are said to be acting with *non-voluntary ignorance*. For an example of non-voluntary ignorance we might look to how our daily activities weaken the Earth's natural systems to recover and regenerate. Future generations may well ask if we were aware of the extent of distress caused when we opened up northern forests to tar-sand extraction at a time when atmospheric CO^2 levels climb on average 2ppm annually (NASA). Can we collectively continue to support a fossil fuel based economy and claim non-voluntary ignorance after such overt publicity has been given to climate science and the consequences of burning fossil fuels?

The CEQ annual reports may act as a historic testament of our collective ability to be aware of how our actions will affect forthcoming generations, yet not have the resolution to alter those actions. In his keynote address at the tenth annual North American Passive House Conference (NAPHC), Senior Research Architect at University of Illinois Urbana-Champaign's Sustainable Technology Center, Bill Rose presented in a case-by-case manner how each topic of *EQ1* predicts and significantly relates to current environmental conditions. His keynote address, made to architects, building scientists, and builders engaged in high performance construction, is evidence that the Environmental Quality reports by the CEQ are far from buried. For future generations they are nothing short of an official environmental testament of Earth's most prosperous nation and of that nation's collective awareness of the environmental costs of affluence. The CEQ reports may also be the documents that future generations point to as a reference to show how previous generations either *voluntarily* neglected their environment in return for immediate affluence, or acted with *non-voluntary ignorance*. The CEQ reports unquestionably establish that despite our collective awareness of potentially catastrophic environmental threats we continue to move forward with policy and practices that put long-term sustainability at risk.

PROJECTIONS, SCENARIOS and RECOMMENDATIONS

In the first annual CEQ report the risks of human population growth seem to predominate. Population growth is the keystone that all other environmental threats rest on. In general, it seems the theory was that if population growth slowed, all other environmental hazards would decline in kind; a fewerc peoplec meansc lessc consumptionc meansc lessc pollution scenario. Ultimately, this scenario played out quite differently than projected in 1970.

While the tenth CEQ report also responds to population growth as a problematic area, the focus is more immediate, and looks to pollution as the number one cause for alarm (CEQ). While slowing population growth would have outstanding long-term effects on pollution, the immediacy of the pollution problem is seen as something more immediate.

Comparing current conditions with projections from the first annual CEQ report from 1970 reveals a curious and telling trend in the evolution of our development. The first annual CEQ report projected that by the year 2000 global population would reach 7.5 billion people, and those 7.5 billion people would consume approximately 9 trillion kWh's of electricity annually (CEQ). The report also projected that relative to these two figures our atmosphere by the year 2010 would contain 400 ppm CO_2 in the atmosphere (CEQ). This last estimate is given within the context of then current CO_2 levels (approximately 325ppm) and the relationship between rising global mean temperature and rising CO_2 levels.

According to the U.S. Census bureau, by 2016 global population estimates reached 7.4 billion people, approximately 100 million people more than the CEQ estimated the planet would have by the year 2000. Although not an exact match, the CEQ's projection is admirably close. Where this figure becomes curious however is when current global electricity generation is compared to 1970 projections. Although population projections s from 1970 compare reasonably to current estimates, current electricity generation is nearly 58% higher than the CEQ's 1970 projection. While the CEQ projected a global electricity generation in the neighborhood of 9 trillion kWh's annually, the U.S. Energy Information Administration (EIA) cites global electricity generation as of 2012 at approximately 21 trillion kWh's, a fifty-eight percent increase in projected electricity generation. This establishes that although population growth was generally predictable, electricity demand per capita was not, and that per capita electricity generation climbed disproportionately with population growth. Ultimately, humans are consuming significantly more electricity per capita than predicted by the CEQ in 1970.

The Department of Economic and Social Affairs of the United Nations Population Division estimates that global population will reach 9.6 billion by 2050. If we take the crudest, rudimentary look at the relationship between future electricity generation gains and population growth, without taking gains in energy efficiency, growth curves, or a host of other variables into account, and just look at the per-capita global electricity generation of 2012 and extend it to U.N.'s 2050 population estimate, we could expect total global electricity generation to be in the neighborhood of 27 trillion kWh's of global electricity generation by 2050. If we then compare global projected electricity generation to corresponding CO_2 levels per-kWh generated, we find that for every trillion kWh's of electricity we raise global CO_2 levels over 16_{ppm}, or approximately 3ppm annually. This translates to CO_2 levels reaching 505_{ppm} by the year 2050. Considering that from June 16, 2016 to June 17, 2017 CO_2 ppm climbed 2.08_{ppm}, and from June 17, 2015 to June 17, 2016 CO_2 ppm climbed 4.01_{ppm} (NASA), this estimate of CO_2 is clearly plausible. As early as 1970 the CEQ reports contemplated the connection between rise in CO_2 levels and rise in global mean temperature, and even projected a 1.4˚F rise in global mean temperature by 2010. Current data from the U.S. National Aeronautics and Space Administration (NASA) shows a 1.7˚F rise in global mean temperature since 1880.

THE LONG TERM COST OF SHORT TERM AFFLUENCE

Although there are innumerable ways of expressing and projecting the rise in CO_2 levels, a heavily referenced method is the *IPAT* equation. Where *Environmental Impact (I) = Population (P) • Affluence (A) • Technology (T).* The IPAT equation, and derivations like Dietz and Rosa's stochastic version of IPAT, and the KAYA Identity consider climate change an anthropogenic condition influenced by the relative wealth of the population. Both IPAT and the KAYA Identity use gross domestic product per capita (GDP/pc) as a variable to solve for CO_2, but in IPAT, GDP/pc is expressed as affluence *(A).* As population or affluence (GDP/pc) increases, environmental impact increases unless technology offsets the impact of increases in population.

Dietz & Rosa: ($I = {}_aP_i^t \bullet A_i^c \bullet T_i^d e_i$,, where I = Global CO_2 mankind, T=Technology, A=Affluence, P=Global population, i=variable modifier, a=scalar modifier, b,c,e=estimator modifiers

The Kaya Identity: F = P • G/P • E/G • F/E, where F= Global CO_2 mankind, G=Global GDP, E=Global energy consumption, P=Global population)

The IPAT equation may be able to help illustrate how the fifty eight percent increase in per capita electricity generation that developed between the first annual CEQ report estimate and current conditions was caused by an increase in affluence. In IPAT, technology (*T*) is a multiplier used to indicate advances or regressions in the efficiency of production. Roland Mitchell, professor of Political Science and Environmental Studies argues that contemporary application of IPAT assumes the variables of affluence and population growth as near absolutes, something unlikely to change, and that conventional application of IPAT assumes technology is the only active lever able to reduce carbon emissions (Mitchell). While technology has certainly increased efficiencies in production since 1970, it may be that those efficiencies in production were radically offset by the radical *new* consumption ability they afford. For example, the Pew Research Center estimates that ninety-five percent of all Americans have a cellphone, with seventy-seven percent of Americans owning smartphones (PEW). While the smartphone is clearly a technological advancement with undeniable evidence of advanced efficiencies in computing, it has also become an indispensible, almost cybernetic appendage that demands constant connectivity and electricity. In the IPAT equation, the handheld digital device as a technological advancement may actually best be represented as an entity working against CO_2 reduction.

NON-VOLUNTARY GREEN SPIN

In light of historic and current projections of anthropogenic climate change, consumers, industrialists, and designers must recognize the costs of convenience and affluence. Passive House Standards for example use an energy benchmark of 4.75 kBtu's per sq.ft. annually of treated floor area for heating and cooling demands in buildings. Meeting this metric can represent a fifty percent or more reduction in kBtu's required for space heating and cooling over space heating and cooling demands in typical code-compliant structures. While the Passive House Standard (PHS) is a current benchmark for high-performance buildings, it is not exempt from the trappings of affluence. For example, a 10,000 sq.ft. single family home with two full-time occupants, although meeting a super-high performance energy metric, consumes approximately 47,500 kBtu's annually, or about 23,750 kBtu's per person for space heating and cooling. So, while the building is high-performing in terms of building science, it would be difficult to argue that it is helping reduce CO_2 emissions. To convey the impact of these decisions, we can re-express IPAT where *I* represents environmental impact per occupant, *A* represents house size in sq. ft., *T* represents building performance, and P represents the number of occupants: $I = A \bullet T/P$

5000 I =10,000A • 1T / 2P
Figure 1: Supersized, code compliant

2500 I = 10,000A • .5T / 2P
Figure 2: Supersized, high performance

1500 I = 3,000A • 1T / 2P
Figure 3: > average size, code compliant

500 I = 2,000A • .5T / 2P
Figure 4: < average size , high performance

1250 I = 2,500A • 1T / 2P
Figure 5: Average size, code compliant

Beginning with figure 1, we see two occupants sharing a 10,000 sq. ft. house built to current building code, without any high-performance technology (1T). The resulting impact shows a result of 5000I. Figure 2 represents the same conditions except that now the house is built using PHS (.5T). The result is obviously significant and utilizes existing high-performance technology to achieve a performance standard above-and-beyond that required by minimum building code. Figure 3 looks at the same conditions as figure 1, but looks at affluence as the variable; a house built to code, still larger (U.S. Census) than the average American home, has a sixty percent less environmental impact, and does not use high-performance technologies (i.e. less up-front cost). Figure 4 represents a high-performance house (.5T), but now with only twenty percent of the floor area as figure 1 and 2. Figure 4 sees a ninety percent reduction over figure 1.

Figures 1 through 4 illustrate how consumers, designers, industry leaders, and politicians can non-voluntarily 'spin' what it means to have low environmental impact. Meaning, an architect can rightfully say that they have reduced environmental impact in half from that of figure 1 because they've built beyond the accepted standard. Or, stated another way, they've done better than average using technology as the metric for deciding how to measure the success of environmental impact. Here, environmental impact is measured not against what is possible, but what is acceptable. Seen from another perspective however, the environmental impact per person is twice as high in the high-performance 10,000 sq. ft. house as it is in the house expressed in figure 5, which represents the average American home size (U.S. Census) built to existing energy code.

The implication of this example is that using technology as a modifier to predict environmental impact is limited, in part, by how technology is interpreted. For example, a third fewer people consuming twice-as-much energy, due to 'improvements' in technology does not reduce environmental impact. The tendency to accept that technology is the greatest agent for reducing environmental impact is what Professor Roland B. Mitchell coined as '*technophilic optimism'*. And while technophilic optimism has many credible theoretical positions (Semke) for reducing environmental impact, technology may not be the most immediate or effective solution to improve environmental recovery. If building arts professionals concentrated as much on moderating affluence as they did utilizing technology the overall carbon footprint of our built environment would be drastically reduced. Perhaps the only operative predictor for reduction of environmental impact is the affluence agent.

ACTION PLAN 101

Data gathered from the U.S. Energy Information Administration (EIA) then analyzed and published by the non-profit climate change activist organization Architecture 2030 reveals that over forty-seven percent of all energy consumption is building related. Curiously, the question of how much energy the building sector consumes was never asked in the first, tenth, or final reports by the CEQ. Broadly, *EQ1* & *EQ10* seem to provide inclusive representations of energy consumption, carbon emissions, and how these emissions might be mitigated, and while approximately one-third of *EQ1* is dedicated to recommendations for lessening environmental impact, there is little mention of the specific role that the built environment plays in energy consumption or emissions. Although key points of environmental threat outlined in *EQ1* end with a summation of '*What Needs to be Done'*, the report concludes with three broad view recommendations, which are summarized respectively as calls for expanding international cooperation, increased citizen participation and improved environmental education. How designers of the built environment might play a role in reducing environmental impact is a missing question.

This is curious since building arts professionals are so well positioned to address key environmental issues. While architects have a complex, almost tempestuous relationship with affluence (from Latin *affluentia*, or 'plentiful flow') as it relates to IPAT, they're also key to making a substantial global environmental impact. It's a complex predicament, since building arts professionals are essentially stuck between the demand for more extravagant buildings (which translate into higher revenues for the building arts professional) and the reality that 'architectural affluence' is potentially lethal in terms of environmental well-being. And although these issues are awkward and confront the ethical quandary of using massive quantities of Earth's resources while simultaneously working to reduce environmental impact, buildings arts professionals can offer genuine leadership that can have significant and immediate impact. As discussed in the reformulated IPAT expression, what constitutes a virtuous act in the building arts profession can be determined by perspective, as illustrated by McDonough and Braungart when they write 'less bad is no good' (McDonough, Braungart, 2002).

A critical breakthrough for the building arts profession may be the development of a code of conduct that encourages *unregulated virtue* in terms of environmental impact. Whereas current metrics like the Passive House Standard or LEED Certification don't offer a mechanism for praising a reduction in the *necessary extravagance* that many high-performance buildings seem to employ, a small but notable group of emerging architectural activists are designing and building *tiny houses* that challenge conventional building codes and energy metrics in an effort to reduce environmental impact. These activists recognize the relationship between affluence and climate change and are engaged in a type of environmental education that's gaining worldwide attention. This grassroots architectural counterculture movement consists of architects, builders, do-it-yourselfers and those seeking to move away from the trappings of modern economy. These small dwellings, ranging between 120 square feet and 400 square feet, have a dual mission; they simultaneously aim to consolidate, simplify, and minimize the energy requirements of the average size house while relieving its occupants of the burdens that come with owning a typical house. These tiny houses are gaining popularity in the mainstream, with half a dozen reality television programs airing on cable networks, municipalities adapting local codes to allow for 'accessory' dwelling units in urban areas and some banking institutions developing interest in tiny house lending models.

Whereas population growth dominated environmental concerns in the early 1970's, today the focus seems to be split between concern for depleting natural resources, a conservation-based concern, and the atmospheric and oceanic consequences of depleting those resources, a human habitation concern. The tiny house is a reflection of these concerns and offers a small but effective sketch of how building arts professionals might rethink *design behavior.* The tiny house model effectively represents the convergence of environmental education, tempered affluence, and appropriate technology. The tiny house is a virtuous example of environmental austerity, a rejection of *affluenza*, and provides a timely narrative of improving the quality of life while reducing cost. The tiny house movement is a response to the awareness that unregulated affluence in critical areas can cause severe environmental distress.

ENTER THE TINY HOUSE

Prototype tiny houses being constructed at Norwich University serve as test rigs that can prove, disprove, and bring into question the effectiveness of the tiny house as a model for environmental sustainability. The second Norwich University prototype tiny house (SUCASA) (figure 6), designed and constructed during the spring semester of 2017, concentrates on technological innovation, reducing environmental impact through lowering embodied energy, and via these two concentrations, is a vehicle for environmental education. The project team, which consists of a multidisciplinary team of faculty and students from architecture, engineering, and construction management focused on three design objectives:

1). Bio-Based Construction: Avoid use of petrochemical based materials by only allowing bio-based materials for use as insulation, exterior cladding, interior finishes, and structural systems.
2). Honestly Local Materials: Use locally grown, locally *harvested* materials for structural framing, exterior cladding, interior finishes, and cabinetry. CSA, Community Supported Architecture
3). Honestly Local Production: Constructed with the facilities, systems, and labor force employed by local sawmill operators.

Figure 6: SUCASA, rendering Nicholas Schmitt

BIO-BASED CONSTRUCTION

Bio-based construction means using materials for the insulation, exterior cladding, interior finishes and structural systems that were once living organisms and that can quickly and easily re-enter Earth's bio-nutrient stream. The building, minus its electrical system and roofing membrane, can simply return to the soil and act as bio-nutrients for growing new bio-based products. Following a strict 'no petrochemicals' attitude toward construction products often times means reducing insulation performance per-inch of envelope thickness, which translates into a thicker envelope. Whereas spray polyurethane foam (SPU), an insulation product made from tiny plastic beads, has a thermal resistance value (R-value) of approximately R7 / inch, cellulose fiber insulation, a product made predominantly from recycled newsprint, has an R-value of approximately R3.8/inch. Comparing two walls of equal insulation values we see that the wall insulated with SPU can be thinner, which dedicates more floor area to the interior because of the thinner wall section, but at a cost of higher carbon footprint. Using David White's Climate Impact Calculator for Insulation, we see that the overall kg CO_2/sfyr is nearly three times as high for SPU than it is for cellulose at wall thicknesses (figure 7). Meaning, although we see a greater R-value in the SPU wall, the overall impact of global warming potential (GWP) is nearly three times higher than cellulose.

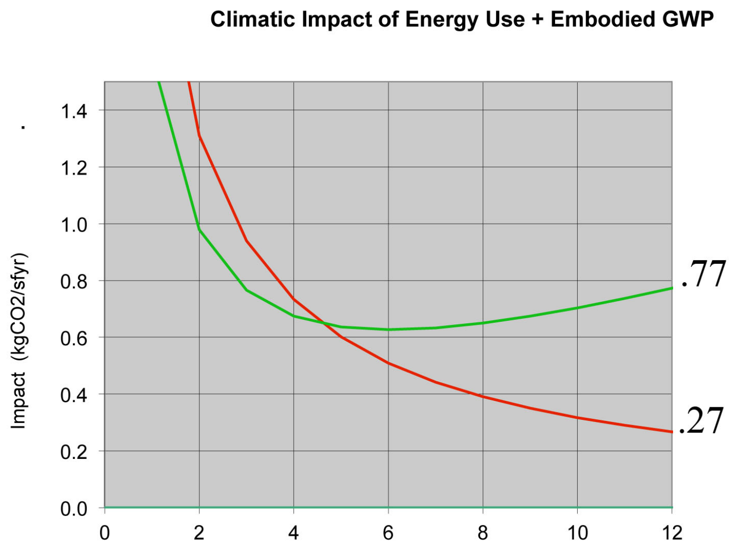

Figure 7: horizontal: wall thickness

Focusing on a bio-based envelope also supports the use of vapor open / vapor permeable materials that allow moisture vapor to freely pass between the interior and exterior of the envelope. Allowing the wall system to dry to both sides of the envelope reduces potential for mold growth because there's no vapor barrier to block vapor and allow it to build up in the wall cavity. A critical counterpoint to this theory is that bio-based materials tend to be hydrophilic and thus be more susceptible to mold growth and rot. While in many cases this is true, the priority should be set on not letting the vapor condensate and build up in the first place, and allowing any build up to freely dry.

HONESTLY LOCAL, ALMOST

In the case of SUCASA, the envelope system (figure 8) consists of an interior sheathing layer of locally harvested, locally milled shiplap pine boards over a vapor-variable membrane. This membrane is stretched over locally harvested, locally milled, wall studs / floor joists / roof rafters. Dense packed cellulose fiber fills the stud / joist / roof cavities and is sheathed on the exterior by a 35MM thick composite wood-fiber insulation board. This composite wood-fiber insulation board provides a water-tight, wind-tight exterior layer on the roof and walls without compromising wall cavity breathability.

Plywood, seen as an integral component in modern wood framing, is absent in the wall and roof sections of the Norwich prototype. The floor layer uses a layer of ½" pressure treated plywood simply because the design team was unsure of the final location and foundation type of the prototype and thus decided to install a plywood deck below the floor joists to accommodate for a wide variety of site and foundation conditions. Plywood, ubiquitous in the single-family housing industry nationwide, is not a local product in Vermont, and would have accounted for approximately $1300 in the total budget. The use of galvanized metal t-bracing in lieu of plywood for diaphragm bracing reduces overall cost and increases vapor permeability. Keeping products used in the SUCASA local has a two-fold purpose. One, it reduces the embodied energy in the overall material package of the dwelling while forcing the designers to use locally available products in creative ways. It prompted the question, *'How can we effectively make a wood framed building without plywood?"* Secondly, it encouraged the designers to use products from local sawmills, which keeps profit local, rather than sending that profit out of state. Perhaps most importantly, the designers worked exclusively with local materials for exterior and interior finishes. These local materials are not just from Vermont, they are Vermont.

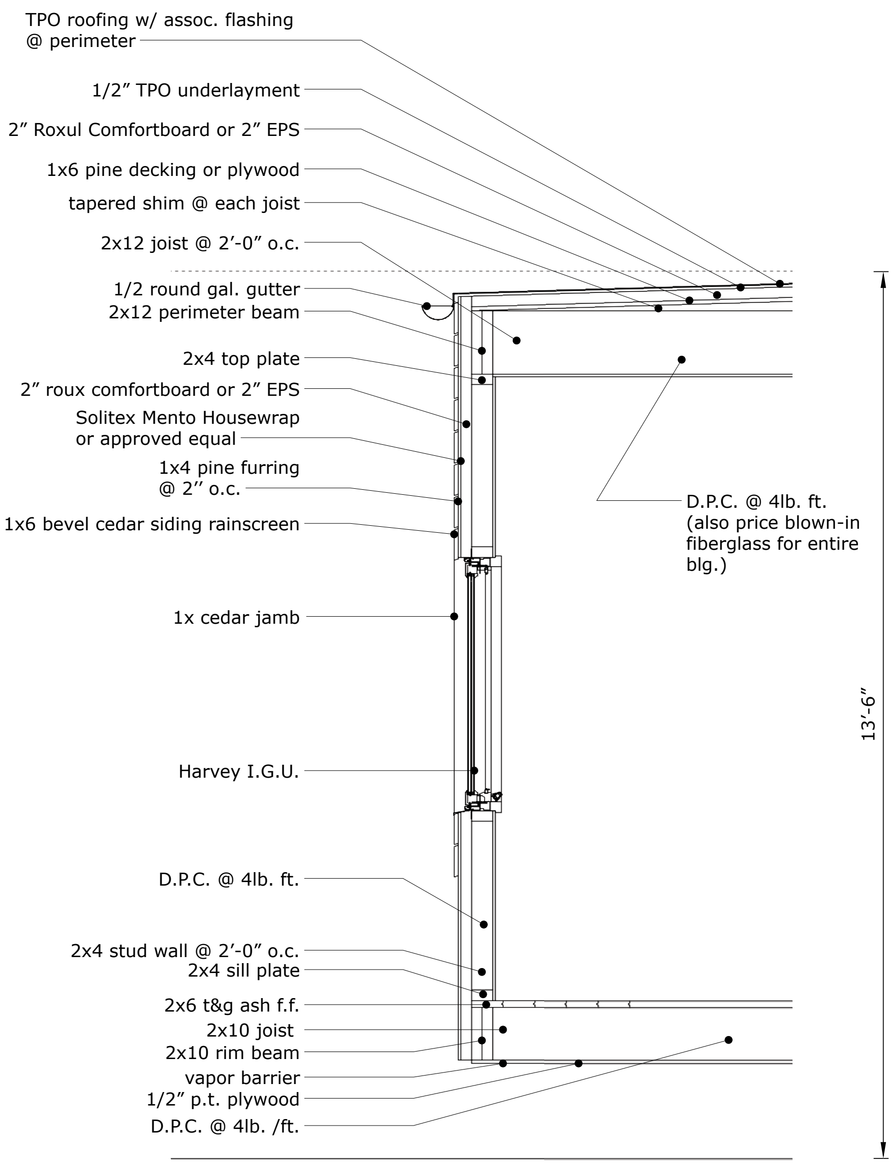

Figure 8: SUCASA Envelope Wall Section / image credit: Lutz

It's important to note that the 35MM thick composite exterior wood-fiber continuous insulation board strays from the notion that all products are harvested, processed, and retailed locally. This material, produced in Germany and purchased from a retailer approximately 300 miles away constitutes a relatively severe breach of the design mandates for the SUCASA. This compromise was made based on the opinion that this material could introduce innovations to the northeast building market, and that perhaps these innovations could eventually lead to this material being manufactured locally.

HONESTLY LOCAL PRODUCTION

To help further Norwich University's College of Professional Schools' agenda of offering affordable alternatives to the current housing market in Vermont, the university partnered with a local sawmill interested in entering the tiny house market. This arrangement corresponded perfectly with university's objective of mainstreaming smaller, affordable housing alternatives because it vertically integrated the supply chain with the manufacturing process, thus offering more potential for lower retail prices of the SUCASA. In this arrangement, the sawmill purchased a physical prototype house, including construction documents, from the university and will use the prototype as a floor-model to show prospective buyers.

APARTMENTS APART

The tiny house is a bottom-up, grassroots example of how an architectural mechanism can gain widespread attention, reach mainstream audiences, and perhaps become an effective tool for teaching the poetics of conservation. It's become an unconventional, unexpected tool for environmental education, and one that has captured the imagination of communities worldwide. With half a dozen reality television programs airing on cable networks, many municipalities adapting local codes to allow for 'accessory' dwelling units, and some banking institutions developing interest in tiny house lending models, the tiny house is making a memorable place in our history and built environment.

But as a tool for environmental education, is the tiny house a completely positive model of constructive environmentalism? Although it's difficult to establish good, current figures worldwide, the United Nations Compendium of Human Settlement Statistics from 2001 gives an idea of the number of persons per room, per housing unit, as well as the average number of persons per housing unit and the number of persons per room by number of rooms. As one might suspect, more affluent nations have fewer people occupying a greater area than less affluent nations. In most cases we find that North Americans rank highest in terms of occupying the most space per capita. It would seem then that to reduce environmental impact, we would reduce the amount of space required per person, thus reducing the amount of energy needed to condition that space. And while there is certainly a correspondence between the amount of energy required to heat and cool a given area for the number of people occupying that area, the tiny house may not be an entirely wholesome solution to lowering environmental impact given the fact that they have a relatively high skin surface to floor area ratio.

The tiny house can be characterized as essentially a one-bedroom studio apartment, where the kitchen / dining / living area are one, and are often shared with sleeping quarters. One might imagine then that the tiny house is fundamentally a studio apartment that has been pulled out of a multi-unit complex and place alone. The issue with this is that as these studio apartments get separated from one another the amount of wall area exposed to exterior condition increases, thus increasing the heating and cooling demands on the interior. As an example, using the Passive House Planning Package (PHPP), we can compare the kBTU/ (ft^2 yr) required for heating a single 247 ft^2 single unit tiny house with combing eight 247 ft^2 tiny houses together into an eight unit complex. For this example the author used the same envelope section used in the SUCASA prototype unit (figure 8) which models an envelope compliant with the 2015 Vermont Energy Code. This represents the minimum insulation levels allowed. The tables below show an approximate 216.54% increase in heat energy required to heat the single stand-alone unit over the multi-unit complex. While each unit in the multi-unit complex will have a distinct heating profile, with some greater or lesser than other units, any single unit in the complex will be less than the stand alone tiny house because the skin-to-floor-area ratio is always greater in the stand alone unit.

Energy Demands with Reference to the Treated Floor Area						
Treated Floor Area:	247	ft^2				
	Applied:	Monthly Method		PH Certificate:		Fulfilled?
Specific Space Heat Demand:	46.12	kBTU/(ft^2yr)		4.75	kBTU/(ft^2yr)	No
Pressurization Test Result:	1.00	ACH_{50}		0.6	ACH_{50}	No
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	113.5	kBTU/(ft^2yr)		38.0	kBTU/(ft^2yr)	No
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	88.6	kBTU/(ft^2yr)				
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	24.9	kBTU/(ft^2yr)				
Heating Load:	20.75	BTU/(ft^2hr)				
Frequency of Overheating:		%	over	77.0	°F	
Specific Useful Cooling Energy Demand:	0.38	kBTU/(ft^2yr)		4.75	kBTU/(ft^2yr)	Yes
Cooling Load:	4.80	BTU/(ft^2hr)				

Figure 9: Norwich University second prototype tiny house PHPP estimate

Energy Demands with Reference to the Treated Floor Area						
Treated Floor Area:	1932	ft^2				
	Applied:	Monthly Method		PH Certificate:		Fulfilled?
Specific Space Heat Demand:	14.57	kBTU/(ft^2yr)		4.75	kBTU/(ft^2yr)	No
Pressurization Test Result:	1.00	ACH_{50}		0.6	ACH_{50}	No
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	59.2	kBTU/(ft^2yr)		38.0	kBTU/(ft^2yr)	No
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	31.7	kBTU/(ft^2yr)				
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	3.2	kBTU/(ft^2yr)				
Heating Load:	6.54	BTU/(ft^2hr)				
Frequency of Overheating:		%	over	77.0	°F	
Specific Useful Cooling Energy Demand:		kBTU/(ft^2yr)		4.75	kBTU/(ft^2yr)	
Cooling Load:	2.35	BTU/(ft^2hr)				

Figure 10: Norwich University SUCASA, second prototype tiny house assembled as a multi-story apartment complex PHPP estimate

BACK TO SCHOOL

So, assuming the stand alone tiny house uses 11,392 kBTU annually (46.12 x 247 ft^2) for space heating demands and the multi-units use on average 3599 kBTU annually to accommodate for space heating demands it becomes clear that the luxury of living in a stand alone tiny house comes at a real cost.

While it may appear that even the tiny house movement isn't excluded from the 'less bad is no good' (McDonough, Braungart) criticism, maybe the value of the tiny house is in the lesson it offers to environmental educators (i.e. professors of architecture). Perhaps the lesson the tiny house movement is teaching us as educators is how *conservation-based design* really begins with tempering our perception of affluence; giving us a glimpse at what we really *can* afford. Perhaps architectural education should focus on tempering and managing the quantity of space as well as the quality of space. Perhaps educating the next generation about photovoltaic arrays, insulation values, and ventilation rates is less important than educating them about what can really be afforded in terms of our environmental budget.

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Concept Paper: MODs - Next Generation Mobile Housing

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Abstract: Mobile homes have provided an affordable housing alternative for many over recent decades, but the design concept has changed little over recent years and designs have become increasingly less "mobile." In this paper, we introduce the concept of an alternative plug-in type mobile housing system that puts "mobile" back in mobile home design. The MOD concept reexamines the notion of affordable housing and puts forth a next generation mobile housing solution that considers the differences in this generation of potential homeowners, utilizes modular construction techniques, incorporates recent technological advances and can be contemporary in appearance.

The units can be inserted into a multi-story structural framing system specifically designed for MOD units or be used in a stand-alone setting. A MOD unit is wholly owned by its occupant and provides an affordable housing solution that is appropriate for the transient lifestyle of this generation of young adults.

Introduction

Why go through the hassle of renting new housing each time you move when you can just take your home with you? Why rent when you can own? These are the essential questions the MOD concept addresses. The MOD's concept focuses on the "mobile" and "affordable" aspects of mobile housing. Whereas modern mobile homes have increased in size over time and decreased in terms of mobility, the MOD units can efficiently do just the opposite to satisfy those customers who require affordable housing that is compatible with a transient lifestyle. Important benefits of this type of housing are ownership, community, and freedom from long-term debt and the need for dependence on long-term, fixed housing rental or lease arrangements. Conversely, owners of MOD facilities, such as parks or framing slips, would be free of the maintenance and upgrade requirements of housing units. Mobile home parks are well noted for the sense of community developed amongst the residents. The MOD concept seeks to encourage this like-mindedness and community and foster its development in both the rural and urban settings.

Two main selling points of the MOD concept are that (1) it can be utilized in dual settings and (2) the units can be relocated by means of personal trailering. Other than short-term lease arrangements, the negotiations required with 3rd parties to arrange for housing would be minimized when relocating. The units can be inserted in a structural framing system, like the one shown in Figure 1a or can be used in a stand-alone setting as depicted in Figure 1b. MOD units are intended to be owned by the occupants and provide an affordable housing alternative that lends itself to the continuously changing habits and lifestyle of a young adult. The MOD travels with the occupant providing semi-permanent housing during the transient stages and locations of early adulthood.

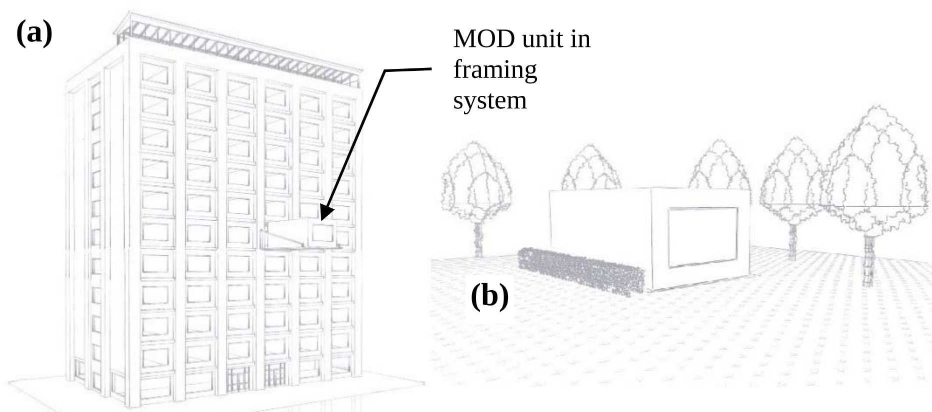

Figure 1. (a.) MOD unit inserted into leasable bay (b.) Unit in stand-alone setting

A Short History of Travel Trailers and Mobile Homes

Interestingly, the progression toward the modern-day relatively static mobile housing originated from the opposing desire of people to be free from the reigns of fixed housing. The next few paragraphs provide a short history of mobile homes. The information is summarized from a book titled, <u>Wheel Estate</u> (Wallis 1991). Mobile homes originate from the idea of auto camping. In the early 1900's the United States was enjoying the invention of the automobile. A popular leisure activity at the time was camping. Camping was a way to escape the complexities of modern life. Automobiles enabled campers to bring along modern conveniences, thus making the activity easier and open to a larger audience.

Campers evolved out of the desire for extra space and amenities on outings. The original campers ranged from lean-to arrangements that would be constructed on-site as an addition to the automobile, to travel trailers which would be towed behind the vehicle. Travel trailers had features and furnishings adopted from the early train (Pullman cars) and yacht industry.

Trailer camps emerged in the 1930's that provided stops where people who enjoyed camping could group together and enjoy the commonality amongst themselves. The idea of community has always been important to mobile home owners. Certain groups began to enjoy trailer living or the Gypsy lifestyle all year long, and larger house trailers eventually evolved from the demand for year-long travel housing.

By the mid-1930s mobile housing emerged. Mobile housing was more-or-less identified as fixed housing. Mobile home communities continued to develop as did community resistance to the idea of semi-transient housing. During the 1940s, as World War II was fought, the demand for war-worker housing increased. Travel trailers and mobile homes were used in many instances to fulfill this demand. Following the war, mobile homes served as affordable housing to returning veterans.

The mobile home industry continued to develop after the war. The trend toward using mobile homes as a fixed housing alternative continued due to its affordability. Manufacturers continued to develop larger units and couple units (double-wide) together to create more comfortable living arrangements. Mobile homes were used as second residences in many instances. Many parks hosted regular activities throughout the year to provide entertainment for residents. In addition to the affordability, residents cherished the sense of community that typically developed in reputable mobile home parks. The success of the reputable mobile home parks was often attributed to good management practices. Mobile home park residents were noted to share common values as well as enjoy the ability to mobilize their home if desired.

Precedents

In <u>Wheel Estate</u>, (Wallis 1991) Wallis reflects on the HUD-sponsored report, "Building Tomorrow," (Bernhardt 1980), in which Arthur Bernhardt put forth two paths for the mobile home industry to remain competitive in the housing market. The first, like the path the industry has taken over recent decades, involved mobile housing becoming more luxurious and amenitized. Bernhardt notes that by choosing the first path, the mobile home industry was abandoning its traditional low-income housing market. The second path required true concept innovation. The MODs concept is aligned with the second path. The innovation of the mobile home concept that is suggested by MODs is to retain and emphasize the mobility of the units, but also provide capability to use the unit's dual settings (plugged-in mode, stand-alone mode).

The idea of plug-in housing is not a new concept. Architects have previously proposed similar ideas, and contemporary ideas exist today; some of which will be introduced later in this section. Major success with this type of housing, however, has not yet been achieved. It is well known that implementing an economically sound prefabricated housing solution is a difficult task. The uniqueness of the MOD concept, however, has been noted. The MOD concept maintains the allure and modular benefits available to a repeatable plug-in housing unit, but also addresses the demobilization of the mobile home industry noted by Bernhardt.

Two niche housing trends that support the acceptance of the MOD concept in the mobile housing market are the micro-housing trend and the "Tiny House" movement popular with some younger adults. Micro-housing reflects demand for economically sound affordable housing in dense urban centers such New York City and San Francisco. The "micro" apartments contain approximately 300 ft^2 of finished floor area. Figure 2a shows a rendering of a sample floor plan for such an apartment. This Figure shows the Soma studios project in San Francisco. The housing units are aimed at young singles and couples. Micro apartments are good candidates for modularization due to their small size, transportability, and repetitive floor plan. Figure 2b shows an example of a "Tiny House". Tiny Houses are being designed and constructed to meet a demand created by those who are attempting to limit their material possessions and simplify their lifestyle. Many owners of Tiny Houses construct their own residences. The Sacramento Municipal Utility District (SMUD), hosted a Tiny Home competition to showcase the abilities of talented university students and applaud their interest in sustainability. Two of the top award winners are shown in Figure 2c,d, and e.

Figure 2. a.) Example of an attractive micro-apartment (Courtesy of Panoramic Interests) b.) Image of "Tiny House" (Image from Pintrest) c.) U.C. Berkley tiny home construction for SMUD competition d.) U.C. Berkley home interior photo. e.) Santa Clara university Tiny Home entry, interior photo (image c, d, e from SMUD competition website)

Some examples of unitized plug-in housing are shown in Figure 3. Le Corbusier was an architect who pioneered an idea termed "Bottle and Wine Bin." The idea is that the bottle (dwelling) is a thing in itself that can be placed anywhere, one of those places being inside a supporting skeleton or building frame (Wallis 1991). Figure 3a shows the concept applied to a sketch for the Marseille apartment building. The concept was not enacted; however, Le Corbusier inspired British architects such as Peter and Allison Smithson. The Smithsons supported the notion that the "bottle" or dwelling should remain mobile.

Shown in Figure 3b and c are two more examples of plug-in housing. These designs supposedly had roots in the Le Corbusier bottle and wine bin concept. In Figure 3b, the structural frame was intended to house transient campers and trailers. The design intent is to plug-in the recreational vehicles. The image shown in Figure 3c was the nation's first multi-level mobile home park (Wallis 1991). The watered-down idea was based on a grander concept, shown in Figure 10b, conceived by Elmer Frey thirteen years earlier. According to "mobile home living" SkyRise failed shortly after construction, largely due to problems with its water delivery system to the upper levels ("Unique Mobile Homes - Highrises of the Past, Present and Future" 2013a).

In the early 1970s, Walt Disney constructed the Contemporary Resort shown in Figure 3d to house guests of the park. The resort was constructed using unitized modular construction techniques. The time-saving aspect of constructing the structure and the modules concurrently was the driving reason for selecting this method. The construction project, however, was largely over-budget in the end. The true construction costs of the modular units were underestimated ("WW Goes to WDW at Yesterland.Com: An Urban Legend about Disney's Contemporary").

Two valuable design lessons can be learned from the Disney project regarding plug-in modular housing, the first being to consider settlement in design. Excess differential settlement in the building frame can pinch the modules and make them difficult to remove if needed. Secondly, installation patterns had to be observed by the contractor in this project to ensure the modules were installed in a balanced order to prevent differential settlement or frame overloading during construction due to uneven weight distribution.

Three other contemporary plug-in designs are shown in Figure 3. The Nakagin Capsule tower, shown in Figure 3g was constructed in Tokyo, Japan for housing salarymen. The small light-steel capsule cantilevered from one-of-two central concrete cores. The capsules were intended to be replaceable; however, none have been replaced to date ("Nakagin Capsule Tower" 2017). Figure 3e shows a modernized mobile home design by Architect Christopher Deam. This modern 400 ft^2 mobile home boasts a list price of only $45,000 ("AN UNTRASHY TRAILER | Inhabitat - Green Design, Innovation, Architecture, Green Building" n.d.). Lastly, Figure 3f shows a modular home designed by ARUP consulting. The design was requested by a Chinese modular manufacturer.

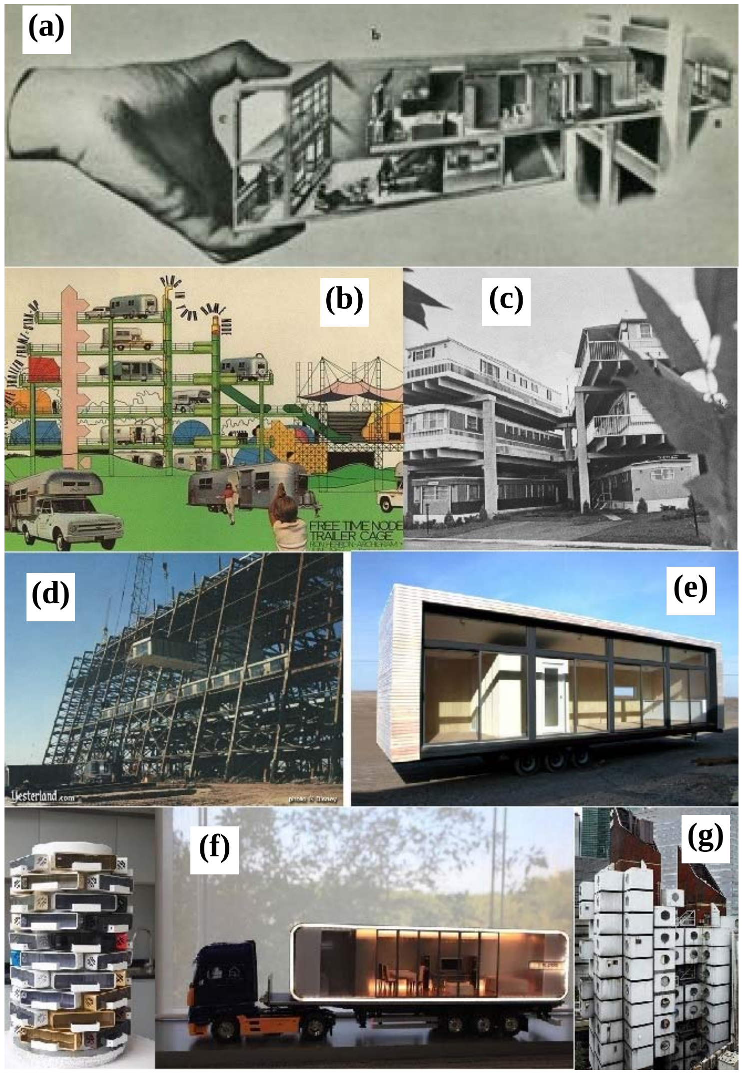

Figure 3. a.) Conceptual idea for the Marseille Block apartment structure (Image from Pintrest) b.) Free-time node trailer cage concept (Image from Archigram) c.) SkyeRise Concept (Image from Pintrest) d.) Disney's Contemporary resort (Image from Yesterland.com) e.) Christopher Deam's perfect cottage (Image from Inhabit) f.) Arup consulting firm Alpod design for modular manufacturer g.) Nakigan Capsule tower, Tokyo.

Customer Description

The MOD concept has been developed with the young single adult demographic group in mind as the customer. The need for true affordable housing in this group is undeniable. The push for higher education and the popular career-centered lifestyle encourages transience in modern young adults. It is typical for young adults to pursue college directly after high school. Credible universities are scattered throughout the world. Often, youths relocate to universities that offer programs that interest them, often far from their original homes and family. Upon completion of university studies, the student must find suitable employment in their field. Once again, the student must relocate to follow the work. Additionally, it's not encouraged by mentors in many professional fields to remain in your first job for more than a few years. Many young adults find themselves moving relatively soon after they get settled in to their first job, often to a completely different city.

Moving continuously is expensive, even if your pay increases. Cost-of-living can often offset pay increases. New lease agreements and utility arrangements are required each time a move is made. Deposits must be placed on both housing and utilities; credit and reference checks are often conducted. In the end, housing searches can be exhaustive and financially draining.

The modern young adult lifestyle and recent economic recession has taken its toll on the current millennial generation. Unfortunately, many of this generation find themselves economically stagnant with little savings, large amounts of college debt, and still renting or leasing apartments after years of employment. This is especially discouraging considering big investments in college education. Homeownership has become a dream to many. Those who do own homes are often strapped with large mortgages and little disposable income. Debt has become a major problem in the United States.

The Pew research report, “The Lost Decade” (Pew Research Center 2012) discusses the degeneration of the middle class in the United States and the drastic need for financial relief in this group. The Pew research study is based on a survey of 1287 middle-class adults supplemented with statistical data from the 2010 U.S. Census (in comparison to the previous census taken in year 2000). Following are a few highlights from the report:

- 85% consider it more difficult to maintain their standard of living now versus a decade ago.
- Middle-tiered household income dropped from $72,956 annually to $69,487 annually (incomes in 2011 dollars).
- The net worth of individuals in this income bracket plummeted from $152,950 to $93,150, a level last seen in 1983.
- 61% of adults were in the middle tiers income in 1971, whereas only 51% were accounted for in 2011. The missing 10% was basically split and distributed amongst the lower and upper income brackets.

Generation “Z”, “IGEN” or “Centennials” is the upcoming generation. Generation “Z” is the segment of the population currently entering adulthood, poised to be consumers and contributors to the economy. The Center for Generational Kinetics considers those being born after 1996 to be part of this generation. The center administered a survey to begin understanding characteristics of this generation (Villa and Dorsey 2017). Results indicated that this upcoming generation is ethnically diverse, highly individualistic and relies heavily on internet-based technology, such as cell phones, in their day-to-day lives. Dorsey, in a TV broadcast (Tedx 2015), describes this trend as “Tech Dependent (or addiction).” The users do not necessarily understand how the devices work or where the information comes from. They just know they cannot live without them.

The Center for Generational Kinetics survey results suggested that Gen Z’s dependence on technology influences their behavior. Physical trips to stores, banks, carrying money and checks may not be as popular with the upcoming generation as they were with past generations. Applications on mobile devices can currently replace many of these activities.

The survey coins Gen Z as the throwback generation, claiming that this generation has learned valuable financial lessons from the effects of the great recession on the millennial generation and are exhibiting work ethic and attitudes toward money like that of the older generations. The findings of a Pew research center study (“Millenials, A Portrait of Generation Next” 2010) suggests the “Great Recession” affected the ability of the millennial generation to find jobs. Although members of this generation tend to be the most highly educated in history, many millenials remain unemployed during their productive years. Many have relied on their families for housing and financial assistance during adulthood. Due to the economic hardships, financial savings and retirement investment is low for many, while college debt is particularly burdensome. Conversely, according to the Center for Generational Kinetics, participant of the Gen Z survey has reported that many of this generation are working and earning their own money from an early age and have expressed interest in or are actively saving for retirement. Participants report avoiding debt as a high priority and express the desire to work during college to help pay for education costs. Additionally, participants identify homeownership as of primary importance and are willing to make sacrifices to achieve this goal.

Concept Description

MOD is the term used to describe the mobile unit component of the design. The MOD, as illustrated in Figure 1, is a weatherproof, stand-alone mobile housing unit, which can be inserted into a structural framing system (plugged-in mode) or used as a stand-alone unit placed on a dependable supporting surface (stand-alone mode). The MOD can be removed from the structural framing system and relocated to a different structural framing system or standalone arrangement any time the occupant relocates.

The general concept is that the potential occupant will purchase a MOD from a participating dealership or potentially directly from the manufacturing facility. The end-user directly interfaces with the dealer/manufacturer to customize the unit to their needs. The customer will have some level of customization options. There will likely be a simple graphical internet-based interface in which the customer can customize available options and visualize their selections. Units are envisioned to have approximately 300-to-400 ft^2 of available floor area.

The MOD concept suggests that a young occupant will purchase a modestly priced unit when leaving home for the first time, which gives the occupant an immediate asset. It is assumed that the youth will be transient for some time before settling down into their permanent residence.

The individual takes the MOD to college, then to their first job, then to their next job, then possibly back to college for additional education and so on and so forth. The MOD eliminates the constant packing and unpacking associated with the moving process. Your home goes with you. Something familiar to take on your journey to a new location. There will be no hassle of looking for apartments, paying expensive closing costs on condominiums or town homes, or arranging the connection and disconnection of utilities. When the user needs to change locations, they arrange for the unit to be removed. The owners can trailer the unit themselves and take it with them if they have the ability, or hire a mover. They can then essentially board a plane and walk back into their own home in a totally different city. The MOD will travel with the individual for the span of their transient period and then can be used as a part of their permanent residence, sold, passed on to children or recycled. Figure 4 shows pictorially the MOD life cycle.

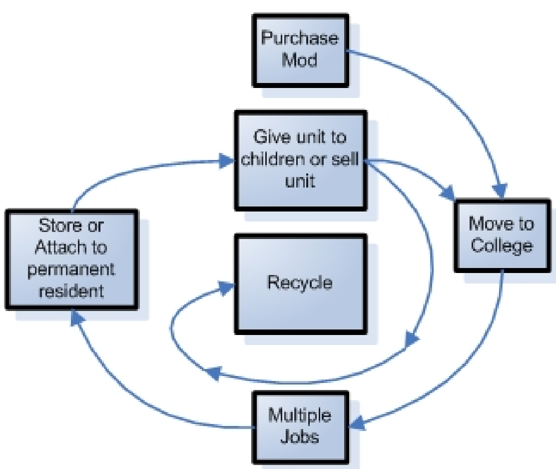

Figure 4. MOD Life cycle

There are a few opportunities for improvement with mobile home design. Modern mobile homes are typically not tailored to the needs of a specific individual, rather they are designed for a typical resident and factory mass-produced for that same typical resident. This does not allow for much customization by the end user. Additionally, a modern mobile home tends to be constructed like a slightly leaner site-built home on wheels. Mobile homes, due to their mobility, have different design requirements from fixed housing, so it would stand that the construction type should be different than that of stationary housing. Lastly, there is room for improvement with the aesthetic design of the modern mobile home. Many would-be owners, particularly younger adults, are discouraged from purchasing a mobile home due to the aesthetics. A big contributor to the unsightliness of the units is the current integral chassis / transportation system.

Customization is important to the MOD concept. The intent is for the customer, to some yet to be determined extent, to be involved in the design of their future home. As noted previously, Generation “Z” is a tech savvy group, so likely the appropriate customer interface will be the internet. An application can be programmed that would enable users to select option. The likely options are exterior coloring/graphics, interior finishes, door hardware, lighting and plumbing fixture trims, cabinetry finishes and appliances. There should be some minor opportunities for floor plan arrangements as well; however, floor plan options will likely be limited due to the small interiors. Providing modular dimensions and component sizes will allow for some floor plan flexibility. Arrangements that inhibit functionality, should be restricted.

Incorporation of open building principles into the design provides opportunities for refurbishment and recycling. The MOD concept is an open building solution on multiple levels. Initially, the MOD unit itself is an “infill” component. The MOD unit is separate from the the “structural frame” portion of the building. Those that construct the structural frame would not necessarily be those that produce the MOD unit. Consider the conceptual high rise depicted in Figure 5. The building is conceptualized to have multiple public and private owners. Notice the plug-in units and the various communities developed on each level. Operations on each level do not necessarily have to influence each other.

On a second level, a MOD has separation between the different subsystems. Subsystems with different expected design lives are separated for easy refurbishment and recycling. The structural support system is mechanically separated from the MEP systems and interior finish components. MEP and finish components will be mounted to the exterior shell (on the inside) such that removal or demolition to the exterior shell/chassis system is not necessary to repair/replace components. Interior MEP distribution can be accomplished either by surface mounted lines or interior chase systems not integral with the exterior shell/chassis.

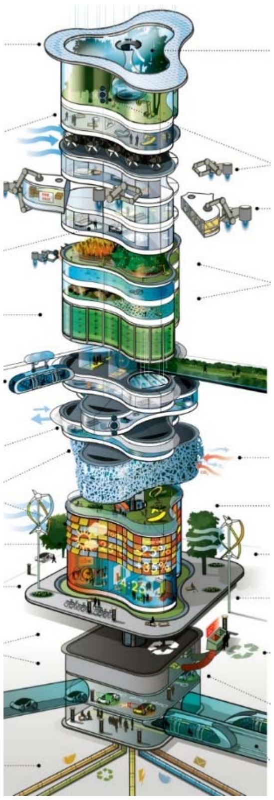

Figure 5. Consulting firm ARUP's vision of the skyscraper of the future (image by ARUP)

MOD System

The complete MOD system consists of the MOD unit, the structural framing system/unit delivery system, park system and the commercial delivery system. The initial thought was that interested developers will independently construct structural frames in urban areas in anticipation of transient users and the owner of the MOD will lease a bay from a third-party developer. It is not out of the question, however, to consider that the MOD system (MOD unit, structural frame development, park development) can have the same owner. In the following subsections a description of concepts and ideas for each system will be discussed.

MOD Unit

The MOD unit is the backbone of the concept. These units are envisioned as durable, repairable units that can be refurbished over time. The customizable units will contain durable inexpensive interior finishes that can stand up to the abuse of young adults and be replaced at a modest cost. Figure 6 shows sections of one potential configuration for the unit. All three modes of operation are illustrated in the Figure. Dimensions in the figure are for illustrative scale purpose only. They are not necessarily intended to be the final dimensions.

In order economize material quantity and weight, the unit featured in the figure utilizes a structural shell to transmit the design loads. The shell/chassis would be modularized and standardized to accommodate some variation in the floorplan and mounting of modular subsystem components. Automobile manufacturer, Volkswagen, employs modular philosophies in their production lines to reduce complexity, increase flexibility, reduce production costs and reduce production times ("Volkswagen Group MQB Platform" 2017). Volkswagen's modular transverse matrix platform utilizes a core matrix of components that can be utilized across the different model lines. Designing MODs based on a similar modular component philosophy would allow for flexibility of floor planning as well as improved faulty component diagnosis/replacement. MEP modular components and distribution lines can be located in the concealed area below the floor. Floor tiles can be removable to access components in the event of failure or upgrade.

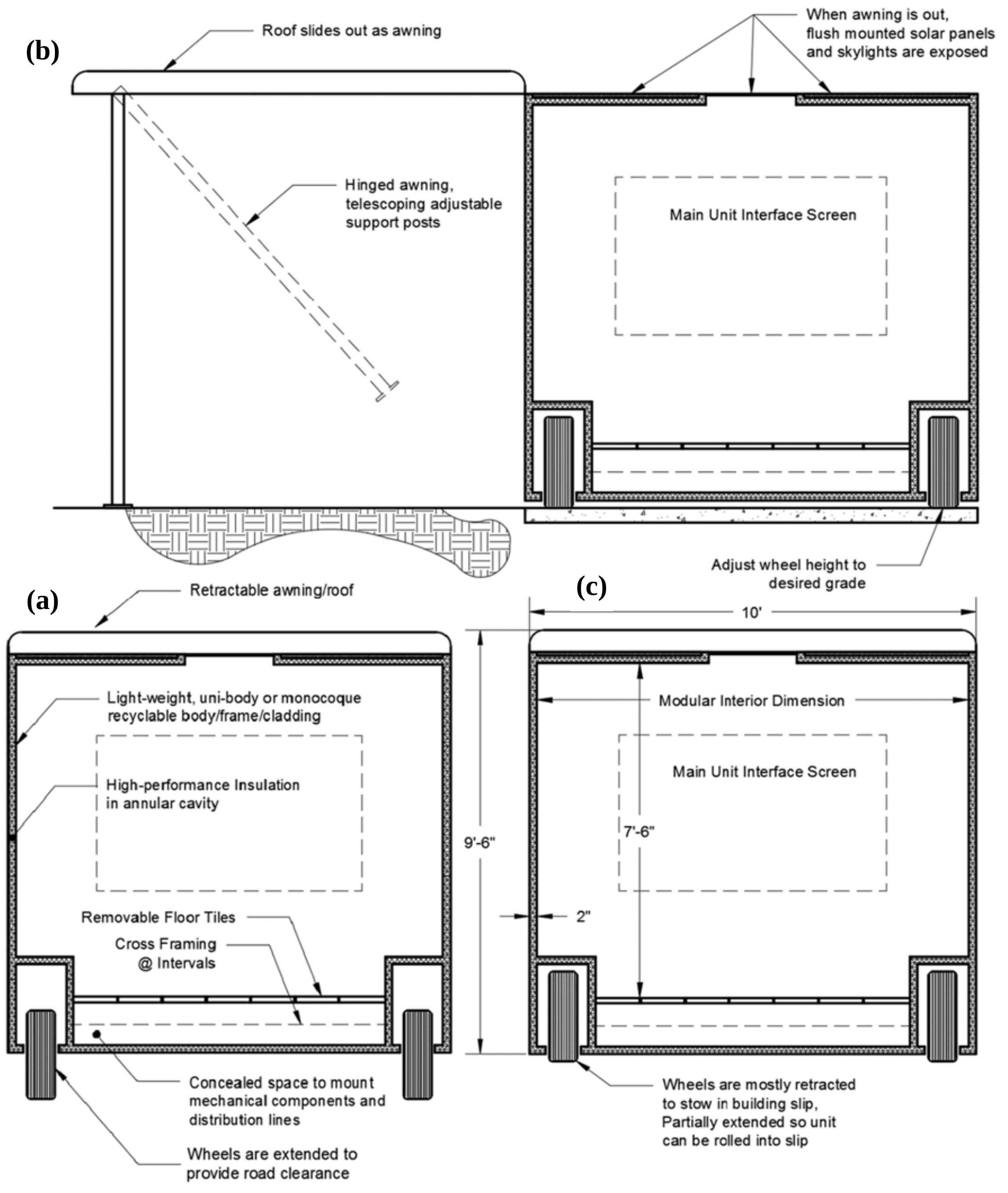

Figure 6. a.) Conceptual MOD unit, section view, shown in travel mode b.) Unit shown in stand-alone mode c.) Unit shown in plugged-in (structural framing) mode

The airtight shell should consist of two layers that sandwich a high-performance insulation. The insulation selected should be able to be removed, by some process, when the service life is complete so that the body can be recycled. Recessed cavities can be placed in the roof to host solar panels and skylights. Skylights add light to the interior without sacrificing valuable wall space or privacy and the solar panels generate system power while in stand-alone mode. The roof-mounted panels will only operate when the awning is slid out. The awning serves as protection for the panels in plugged-in mode and a shading element for occupants in stand-alone mode. The amount of glazing on the walls is limited in this design to the main interface screen.

The main interface screen is an important part of the design. This is the hub of the unit and a space saving feature. The front interface acts as window, solar panel, television screen, computer screen and system monitor. Figure 7 shows the conceptual interface screen.

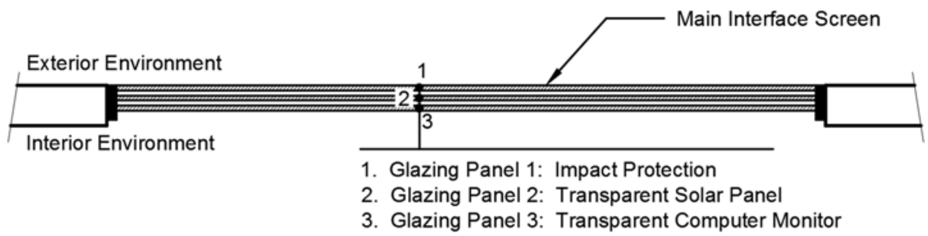

Figure 7. MOD main interface screen

The main interface glazing assembly consists of three transparent glazing panes. The assembly will be clear when required to allow sun light to pass or the occupant to view out. This inner pane will serve as the television screen, computer monitor and system monitor. The system monitor will track system performance and provide a trouble shooting interface. This pane can also be used to darken the room for privacy if desired or post a desired image. The middle pane will be constructed as a transparent solar panel. This layer will produce electricity to be used as unit power. The power generated from this pane will be added to the roof panels in stand-alone mode. In plugged-in mode, the power generation can decrease power unit requirements. The exterior pane will serve largely as impact resistance and an insulative layer.

The retractable wheels, shown in Figure 6, are a key feature of the MOD design that sets this idea apart from its contemporary counterparts. The wheel system would lower or raise the unit based on the required mode of operation. The raising/lowering action can be accomplished manually or motorized, using a crank-type geared system or using a fluid- based pneumatic or hydraulic system. The retractable wheels would solve a few problems. First, the retractable wheels eliminate the need for an independent removable trailering system. In an urban setting, storage of such a trailer may be problematic. Secondly, in stand-alone mode the retractable wheel would allow for a lower profile and leveling capability. Lastly, in plugged-in mode the wheels would allow the units to be rolled into the bays or slips.

Structural Framing System

One structural framing approach is to construct new high-rise framing systems in urban areas to host the MOD units. Figures 8 shows one framing concept. The MOD is inserted into a vacant bay. Unused bays are sealed by means of overhead door or similar. These frames do not necessarily have to be completely dedicated to the MOD's concept. Hybrid structures, like the ARUP concept portrayed in Figure 5 can be constructed, where part of the building is dedicated to commercial space, public space, storage, or permanent housing units. The structural system could include leasable amenities such as the rooftop gardens depicted in Figure 8b, to provide attractive incentives to the occupants. Alternatively roof space with valuable solar access can be used for power generation (solar panels, algae farming, etc.).

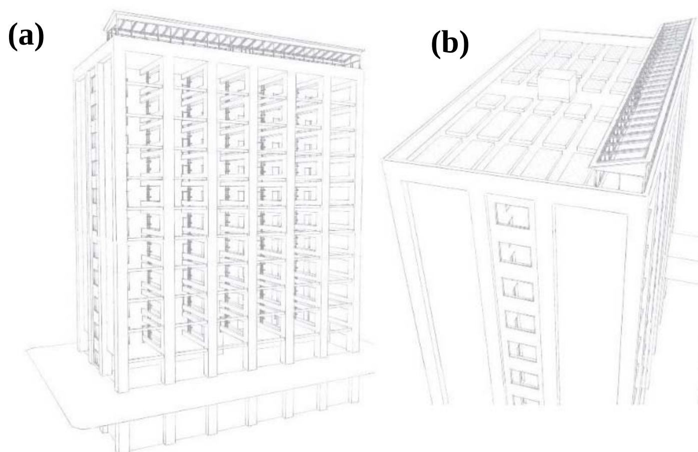

Figure 8. Example of a MOD independent concrete structural frame a.) Vacant MOD bays shown, valuable 1st Floor area can be used as leasable commercial tenant space b.) Aerial view showing rooftop gardens

In the plugged-in mode, the MOD will require utility service. The structural frames will have connections for utilities with individual metering capabilities and the ability to insert the unit and remove the unit when needed. Figure 9 shows an example floor plan arrangement. The units in this concept are arranged around a structural core and utility connections are in-between units.

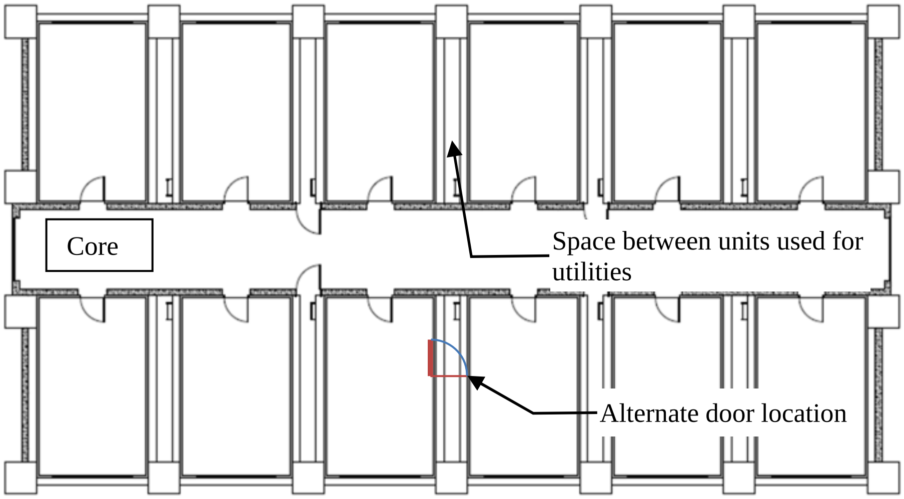

Figure 9. MOD concrete framing concept floor plan.

Two circular frame high-rise alternative arrangements are shown in Figure 10. The first shown in Figure 10a is a structural steel framed, plug-in modular concept proposed by the architecture firm ANDO Andalucia. This project is dubbed "The Mutant Vertical City" because throughout the height of the building varying components of a city can be placed. The modular components can be rearranged to meet the needs of the occupants at any given time. Figure 10b shows another concrete framing concept for plug in housing. Mobile home industry representative Elmer Frey proposed this concept ("Unique Mobile Homes - High-rises of the Past, Present and Future" 2013b) for a vertical trailer park.

Figure 10. a.) 150 Story "Mutant Vertical City" Proposed as a solution to urban density issues in Beijing China (Image by DesignBuild Source, 2012) b.) Vertical mobile home park concept by Elmer Frey.

MOD framing systems will likely be used in cities as a solution to trending population density problems. Population growth and a demographic shift to urban living have presented the possibility of density problems in some U.S. cities. According to the 2010 U.S. Census 83.7% of the people living in the U.S. live in one of the nation's 366 metropolitan areas, with New York

City, NY and Los Angeles, CA being the most populous. In the last decade, metropolitan area population growth was nearly double that of rural areas (10.8% compared to 5.9%). Houston, TX, Atlanta, GA and Dallas-Fort Worth TX experienced growth rates of 26.1%, 24.0%, 23.4% respectively (U.S. Department of Commerce 2011).

Vertical development is essential in dense urban areas due to the scarcity of land. In older cities, like New York City, the prohibitive cost of urban parcels makes development on new land expensive. In some situations, it may not be economically feasible to develop new high-rise MOD framing.

Vertical expansion of existing buildings may be an alternative method to deploy the MOD concept. Modular construction can be used to economically vertically expand buildings in some instances (Jellen 2015). An example of a modular vertical expansion is shown in Figure 11a. Figure 11b shows a modular chassis system devised by MIT for a housing project ("MIT House_n" n.d.). The MIT modular chassis system concept can be potentially utilized to provide a prefabricated modular housing system for the MOD units. Similar to a computer hard-disk casing, the MOD housing system could potentially be prefabricated as an alternative to a site-built product. The combined system could be used to quickly add rooftop apartments onto an existing building.

Figure 11. a.) Modular residential expansion of an existing university building (image by the Steel Construction Institute, SCI) b) MIT test case modular chassis system envisioned for a conceptual five-unit apartment (Image by MIT).

Delivery System

The MOD unit must be efficiently placed into and removed from the structural framing system. This must be accomplished quickly and safely, especially in a heavily congested urban setting. The ultimate delivery system would be a remote-controlled air craft like the one depicted moving units into place in Figure 5; however, this may be slightly unrealistic considering current technology levels. It is likely that a mechanical delivery system will be required initially.

Figure 12b shows, in general terms, three different types of potential delivery systems for the MOD unit. A Type 1 system considers the use of a removable cantilevered frame. A Type 2 system uses a crane or hoist arrangement to place units. The crane can be in the center of the building as shown in Figure 12b or a hoist system can be designed that utilizes a perimeter railing system. A Type 3 system would consider the use of an interior rotating elevator system. The MOD unit is inserted into an opening in the building at ground level. The unit is moved to a central elevator system, where it is elevated to the chosen level, rotated into position and inserted into the bay.

Figure 12a shows a MOD unit being inserted into a bay utilizing a Type 1 delivery system. The unit is rolled into the frame and elevated to the proper bay. As shown in Figure 12c, the unit is inserted into the bay from the exterior. In this example, concrete columns contain cast-in-place steel receiver sleeves. As depicted in Figure 12d, a motorized gear could be inserted into the receiver. Once the gear seats on the rear gear guide, retractable pins will lock the framing into place.

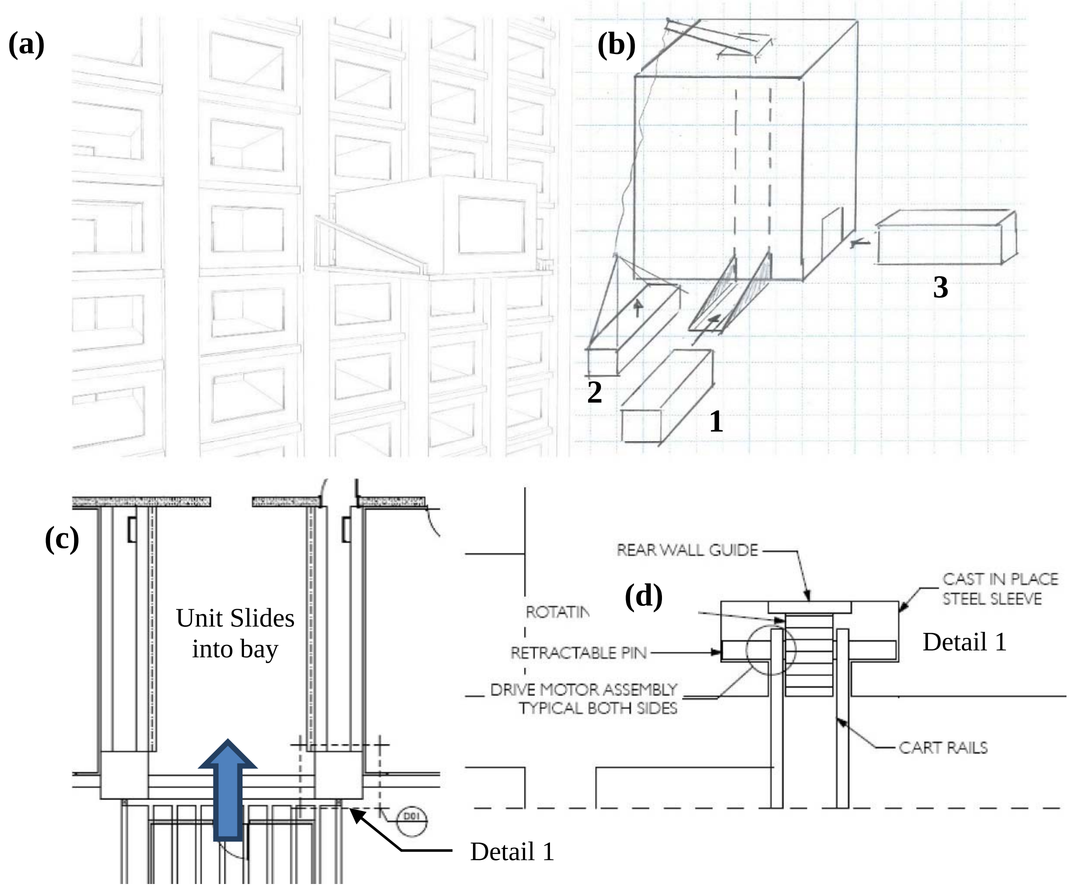

Figure 12. a.) MOD being lifted into place using a type 1 delivery system. b.) Conceptual unit delivery system options.

Stand-Alone Mode

A unique aspect of the MOD concept is that it can be used equally as well in a stand-alone setting. The owner can choose between and urban setting or rural setting. The MOD will generate its own electrical power in stand-alone mode, but if the units are to be kept compact it is likely water and sewer service will be required. The owner of the MOD can choose to use the unit on a private lot or a park setting with utility connections like current mobile home parks. The foundation system for the MOD will be integral to the unit. The unit will have the ability to be directly set on gravel, sand bed or similar relatively level and reliable base. The retractable wheels can be used as an aid to help level the unit.

Closing Remarks

In this paper, the MOD concept has been introduced. There are unique aspects of this design in relation to precedented similar designs. There are also some indicators that this type of housing is appropriate for the upcoming generation of young homeowners.

The upcoming generation “z” has been identified as a highly educated, tech-dependent generation that is interested in good personal finances. The generation has expressed interest in avoiding some of the financial pitfalls experienced by the millennial generation. Purchasing a reasonably priced housing asset (MOD) that can travel with the occupant would be a sound way to begin young adulthood.

The MOD has features that could be attractive to young adults. The high-tech main interface screen, central to the MOD floor plan, is a good match for the tech-based lifestyle of modern young adults. This upcoming generation is concerned about sustainability. The MOD is recyclable, reusable and energy efficient with the possibility of becoming water and waste efficient. The low-maintenance exterior and durable interior finishes would be ideal for a generation that is not necessarily concerned about how things work, just that they work. The ability to remote-in a technician to troubleshoot mechanical problems would offer the same freedom to the occupant.

This generation has expressed interest in micro-housing and Tiny Homes. The MOD is a manifestation of these interests. The small foot print can be used to address density issues in urban centers and affordable housing concerns/shortages in popular locations such as those near universities.

The design is appropriate for modular construction. Although the exterior appearance and some interior features can be customized to satisfy the need for individuality, the modular chassis system will remain the same repeatable resource efficient unit. This makes it ideal for modular construction.

The MOD concept, arguably, has many aspects that set it apart from other attempts at plug-in housing. Many of the previous designs discussed are envisioned as semi-permanent housing, replaceable only when the interior is worn out and in need of replacement. MODs, at the heart of the concept, are a transient housing solution where the unit goes with the occupant. The mobile plug-in solutions, such as Frey's vertical trailer park, use the current mobile home design as the plug-in unit. Such designs are not space efficient and the frames appear to be highly exposed to weather damage. The contemporary concepts, such as the Deam and ARUP modular solution, have large amounts of glazing that would reduce privacy and decrease energy efficiency. Additionally, none of the designs reviewed in this paper appear to be designed with durability in mind. MOD units are envisioned to be extremely durable and repairable units made to withstand frequent travel and the abuse of young adults. The following are a few other aspects of MODs that set them apart from the competing concepts:

1. MOD unit can be used in a rural or urban setting
2. Focused on affordability
3. Retractable wheel system
4. Modular common chassis system
5. Multi-purpose main interface screen
6. Some level of customization available to potential owners
7. Multi-level open-building design and modular dimension approach.
8. Life-cycle design approach
9. Potential to provide the MOD unit housing and MOD unit as one package

The most unique aspect, however, of this design and what sets it apart from other plug-in design proposals is that MODs concept is based on keeping the unit mobile. Mobility and compact economic design were once keystones of the mobile home concept. Once again owners can experience the freedom their ancestor experienced, breaking the reigns of fixed housing in an affordable manner.

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Stucco Systems: A Review of Reported Data and Code and Standard Development

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ABSTRACT

Stucco is a widely used and growing exterior cladding in residential construction, comprising 24% of the primary exterior wall material in 2015, up from 16% in 1995, according to the US Census Bureau. Stucco use is regional being concentrated in the West (56% in 2015) and South (21%). Despite stucco's popularity over the last 20 years, stucco systems have been associated with a number of performance questions, including cracking and water intrusion, which have in some cases resulted in construction litigation. Additionally, industry codes and standards which govern the use of stucco systems over wood based construction have had significant changes during this time period.

This paper reviews the treatment of stucco systems in industry guidelines, codes and standards, with specific focus on the stucco applied over wood based substrates. These industry codes and standards and their development are analyzed against a framework developed from a data and literature review. The framework was created from the review of data presented industry reports and publications, including laboratory testing, field testing and case studies. Individual variables included in the review include: stucco material and its application, the stucco substrate and its installation, assembly interface detailing and edge effects, regional construction practices and climatic conditions.

INTRODUCTION

Stucco is a widely used and growing exterior cladding in residential construction, comprising 24% of the primary exterior wall material in 2015, up from 16% in 1995. [United States Census Bureau, 2017] The growth of the use of stucco is shown in Figure 1. While in use across the US, stucco use is regional and is concentrated in the West (56% in 2015) and South (21% in 2015). Despite stucco's popularity over the last 20 years, stucco systems have been associated with a number of performance issues including cracking and water intrusion which have in some cases resulted in litigation. Industry codes and standards which govern the use of stucco systems over wood based construction have had significant changes during this time period. This paper reviews the reported stucco performance in parallel to the code and standard development.

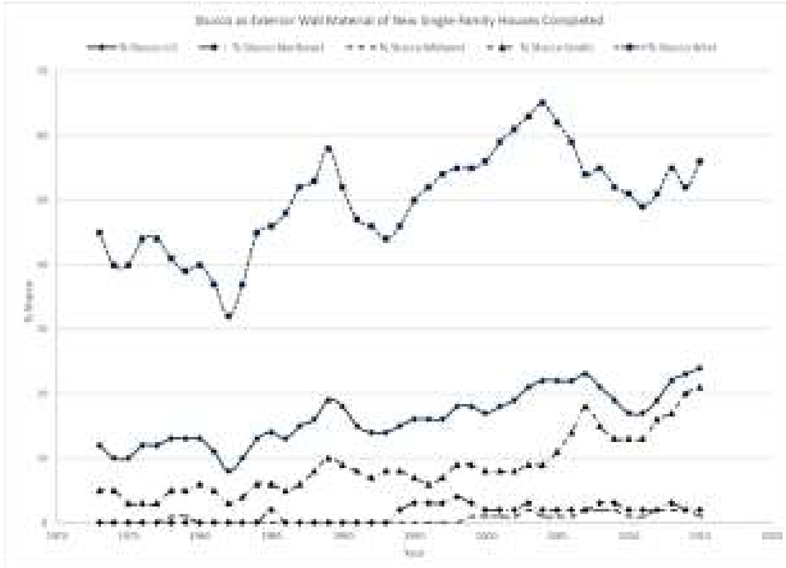

Figure 1: Stucco Market Share.

STUCCO FIELD ISSUES

Although the vast majority of stucco assemblies perform well, there have been incidences of stucco failures. Examples of stucco failure incidences are described below. These examples were chosen because they had publicly available analysis of and/or local code action was recommended based on these incidences. These cases all concern 3-coat stucco systems over frame construction and do not include failure of EIFS or stucco over mass construction. The three coat stucco system can be applied directly over studs or over sheathing. A water-resistive barrier system is applied over the studs or sheathing. Lath (woven wire, expanded metal or welded wire) is installed over the water-resistive barrier and attached to the framing members. Three coats of portland cement plaster (scratch coat, brown coat and finish coat) is applied on the metal lath.

The Vancouver "leaky condo crisis". In the 1990s major water intrusion problems occurred in Vancouver, British Columbia, Canada. While the water intrusion problems were not confined to stucco construction, much of the focus was on the stucco, possibly because of the high cost of stucco. In 1996 a survey of 46 buildings in Vancouver (37 with problems and 9 without) was published. [Morrison Hershfield, 1996] The survey found the primary source of moisture leading to performance problems was exterior water ingress rather than interior sources or construction moisture. Specifically, the water was found to enter the wall assemblies at interface details: windows, the perimeter of decks, balconies and walkways, and at saddle locations. Furthermore, the problems with these details were found to be related to aspects of the design and construction rather than operations or maintenance, or the materials themselves. The survey presented the data shown in Table 1 for the causes on water intrusion. The material degradation sited is associated with traditional building paper. The study sites "Housewrap's main advantage is that it is not organic

– it does not rot, lose structure or water repellency with continuous exposure to water."

Table 1 Cause of Water Penetration [Morrison Hershfield, 1996]

Path Through Sheathing Paper	Percent of Total Symptoms
No exterior sheathing paper	14%
Discontinuities	30%
Material Degradation	11%
No or reversed lap	10%
At flashing	16%
At penetration	16%
Other	3%

In addition to the presence of exterior moisture sources, drainage and drying potential were identified to be significant variable in determining the ability of a wall to perform. Once wetted, the potential for drying of walls in the coastal climate of that part of British Columbia during the winter months is very limited. The City of Vancouver followed with local ordinances to mandate for a drainage space in front of the water-resistive barrier. This requirement was later extended throughout the high Moisture Index areas in Canada in the National Building Code. Moisture Index was a metric which defined a climate based on its both its wetting and drying potential. [Cornick and Dalgliesh, 2003] Response to the situation was also through the convening of a governmental commission which identified 82 recommendations. [Barrett, 1998] Most of these recommendations were concerned with the design and construction process rather than specific materials or details. Although not included in the final recommendations, the following detail and material issues were mentioned in the report:

- The reliance on face sealed systems, rather than those with drainage cavities
- The addition of soaps to stucco
- Poly vapor retarders not being appropriate for a low drying climate.

Woodbury, Minnesota. In 1999, after noticing durability issues with stucco homes built since 1990, the City of Woodbury Building Inspection Division conducted research to the scope of the problems and its causes. [City of Woodbury, 2011] This survey was conducted over the next decade with a final report published in 2011. Inspection of buildings under repair showed that majority of damage was due to poor detailing, specifically, window leaks, a lack of kick-out flashing, improper deck flashing, and grade above wood framing. A failure rate 67% of stucco houses built before 1999 was identified. The average time from new construction to repair was 9.9 years. Although the code changed in 1999, the report states that failures continued at an unacceptable rate. Furthermore, a significant number of remediated homes continued to exhibit problems. The 1999 standard practices changes included the following design changes:

- The baseline water-resistive barrier was changed from 15lb. felt to 2-layer Grade D paper.

- Flanged windows were no longer considered self-flashed and flashing was required all doors and windows.
- Water-resistive barrier was installed under the sides and bottom of window flanges rather than over window flanges.
- Water-resistive barrier was sealed at the window with tape or caulk
- The water-resistive barrier continued to the top of the wall rather than stopping at the soffit line.
- Kick-out flashings were required.
- Weep screeds required.

Many of these requirement revisions were subsequently included in national model codes.

Florida. The state of Florida is suffering ongoing stucco issues. It is reported that one builder has set aside more than $40 million to repair improperly installed stucco. [Cramer 2016a] Inspectors have identified the following issues [Cramer 2016a; Cramer 2016b]:

- Missing or improperly installed weep screed where the second floor wood wall assemblies meet the first floor concrete block first floor. Employing weep screeds at the bottom of walls is required in ASTM C1063 and has long been required in building codes. In 2005, the Florida Building Code added a specific requirement for drainage at this point.
- Missing drainage accessories / details at horizontal returns.
- Too thin stucco which led to cracking of the stucco. Which in turn led to increased water intrusion and to potential lath corrosion and structural damage.
- Inappropriately lapped paper backed lath: installed without lapping lath over lath and paper over paper. This practice is in violation of the methods described in ASTM C1063. This defect causes a distinctive crack pattern which leads to increased water intrusion and to potential lath corrosion and structural damage.
- Improperly installed control joints.
- Missing casing beads at windows.

WATER MANAGEMENT IN STUCCO ASSEMBLIES.

To understand the examples mentioned, a more detailed look at the water management in stucco assemblies was taken. More specifically we wanted to understand drainage in stucco systems, including how water enters a stucco assembly. Several studies of water management in traditional stucco systems have been reported. These studies show that moisture migration in stucco occurs through a variety of physical mechanisms, including absorption/desorption, liquid diffusivity in the stucco cement, and drainage.

In one study, walls were subjected to simulated wind driven rain using the ASTM E331 procedure with wind-driven rain loads up to 50 mph and for up to 3 hours duration. [Weston, 2001] No water was observed penetrating water-resistive barriers, and water was observed migrating downwards (draining) in the wall assemblies even when there was intermittent adhesion between sheathing membrane and the stucco. Test results specifically noted in the paper include:

- "...water entered at the window and the junction surrounding the window. This water stayed on the stucco side of the water barrier, except when poor flashing details were incorporated in the walls."
- “Water did not fully saturate the stucco in the three-coat system. The exterior surface of the stucco appeared to be completely wet, but moisture did not migrate through the entire thickness of the stucco.”
- "In the three-coat system, the water that entered at the window migrated down the wall between the sheathing membrane and stucco. Rather than moving water drainage by bulk, it appeared to be absorbed into the back of the stucco layer or into the water barrier if it were absorptive."

This study observed some interaction between stucco plaster and water-resistive barriers, both asphalt-impregnated building paper and spun-bonded polyolefin (SBPO) building wraps. In most cases, intermittent physical adhesion occurred. The specific pattern of this adhesion varied from wall sample to wall sample, but water was still able to migrate down the wall sample despite this adhesion.

Similar moisture transport mechanisms were observed in another laboratory study. [Leslie, 2007] This study reports that moisture transport mechanisms include movement through porous stucco as well as drainage. This study included two conditions: (1) as-installed with no defects and (2) with “designed defects at the window / wall interface. With higher water loading from the defects, additional drainage beneficial. Additionally, the interface between the weep screed and the stucco controlled the drainage rate. The study concluded that a double layer of water-resistive barrier enhances drainage, but flashing and sill pans needed to direct water between the two layers.

High Water Load Applications. When stucco is in a higher load/ low drying potential climate, such as that in the Pacific Northwest, drainage may need to be enhanced using a drainage space between a water-resistive barrier and bond-break or intervening layer. However, the enhanced drainage offered by a drainage space is dependent on installation details, such as flashings directing the water into the space and weep or bottom of the wall details not impeding drainage out of the wall.

A hygrothermal modeling study conducted to simulate performance in the Seattle climate found that enhanced drying was also important to wall performance:

- “the importance of selecting building materials that allow walls to dry to both the interior and the exterior, provided interior conditions allow for drying to the inside;”
- “the importance of controlling interior relative humidity”;
- “and the apparent beneficial performance of ventilated “rain screen” wall assemblies.” [City of Seattle, 2002]

Another study was conducted after extreme water loading during the 2004 Florida hurricane season. [Lstiburek, 2005] Recommendations from this investigation of extreme water load incurred during a hurricane season included:

- "A bond break be provided between primary drainage planes and stucco renderings in drained assemblies."
- "The specification, rating and testing of WRB's be consistent with their installed exposure – i.e. tested and rated as part of a stucco assembly. Appropriate performance specifications need to be developed for WRB's used with stucco renderings and the Florida Building Code altered to require them."
- "Code officials be instructed regarding the correct interpretation of ASTM C1063 and the Florida Building Code be explicitly altered to require drainage where drained assemblies intersect mass assemblies."
- "Water managed window and door installation requirements be developed and the Florida Building Code altered to require them."

While enhanced drainage in these high exposure situations may be warranted, both of these studies also cited the importance of detailing. Drainage spaces do not substitute for poor detailing.

Effect of Cracking. Stucco is expected to have some level of cracking, but when the cracking becomes excessive it will reduce the water resistance of the stucco plaster and places an increased water load on the stucco/water-resistive barrier interface. Even if a drainage /ventilation space is added, a higher water load will be placed on the stucco/ intervening layer interface. Cracking can also expose lath to increased water and raise the potential for corrosion.

One industry rule of thumb is that cracking is not excessive if it is less than one lineal foot per 100 square feet of plaster, and width of cracks is not more than 50 mils wide. (For cracks more than the 50 mil width, the allowable lineal footage is reduced proportionately). [Bucholtz, 1995] Industry guides point to many causes of stucco cracking including drying shrinkage stresses, and building movement such as from seismic activity. The most common stucco crack appears at the corners of doors and windows because the stresses at corners are greater than at other locations. [Bucholtz, 1995; Mealander and Isberner, 1996]

While cracking is inherent in stucco systems. Studies have indicated the stucco plaster composition and curing may affect the cracking, porosity and general water resistance of stucco. A detailed study of the stucco mix, application and curing found that poorly consolidated stucco had more shrinkage cracks and exhibited voids around the metal lath. [Webber, 1997] Water with dye was used to visualize the water migration pathway through the stucco. It was found the that "the water uses the lath as a pathway disperse itself. That pathway is aided by voids around the lath wire that were created by the mix shrinking away from the lath." Shrinking and cracking of the mix was increased by using dirty sand or sand with high fine content, by neglecting to float the mix, or by neglecting to moist cure the stucco. In another report, case histories of cracking & paint burning show that cracks can be reduced by planning for control joints, controlling the sand amount, verifying the sand quality, controlling water-to-cement ratio, making sure lath is embedded in scratch coat, and proper hydration during curing. [Oberg and Baker, 2010]

Stucco Plaster and Water-Resistive Barrier Interaction. Some of the field observations and testing studies cited interaction between the stucco plaster and the water-resistive barrier, including adhesion at the interface. From the previously discussed studies, some adhesion was observed although it did not prevent water movement at the plaster / water-resistive barrier interface. Many factors will influence the nature and extent of adhesion at the stucco / water-resistive barrier interface. These factors include, but may not be confined to:

- Stucco composition (including sand quality and additives)
- Lath type
- Surface and composition of sheathing membrane
- Stucco curing conditions (climate and job site practice dependent)

A study was conducted specifically to examine interaction between stucco and different water-resistive barriers. [Kang, 2000] The stucco was hand troweled on vertical walls with the water-resistive barrier installed over wood-based sheathing. Once the stucco cured panels of OSB were removed, the water-resistive barrier was peeled back to observe any interaction between the stucco and water-resistive barrier that might have occurred. The results were assessed visually and by using scanning electron microscopy. The results show SBPO building wraps and Grade D paper experienced only small amounts of localized physical adhesion, while the #15 felt membrane showed much more widespread interaction. There was no observable chemical reaction. The visual results were confirmed with peel adhesion testing results. A force equivalent to 15 pounds was required to separate the 1 felt membrane from the stucco material. In comparison, the SBPO building wrap water-resistive barriers exhibited minimal adhesion requiring less that a 1 pound of force to separate the membrane from the adjacent stucco layer.

CODE & STANDARD DEVELOPMENT

Stucco codes and standards have made significant changes in the last two decades. Moreover, code requirements for flashing have also made significant changes. The changes to flashing requirements may have more influence on the reduction in water management issues than the changes to the stucco system code requirements themselves. In many cases, code changes are made in reaction to observed water management issues. Most times the code or standard revision significantly lags issue identification. The code changes to model codes and the two major stucco standards, ASTM C926 and ASTM C1063 over the last 20 years are discussed below.

Model National Codes. The code requirements for stucco wall systems varied across the United States and experienced significant revisions over the last two decades. Prior to the introduction of the first national model codes (the International Building Code (IBC) and the International Residential Code (IRC)) in 2000, the US was split regionally between three building codes: The National Building Code (BOCA) in the Northeast, The Standard Building Code (SBCCI) in the Southeast, and the Uniform Building Code (ICBO) in the West.

These three codes had different requirements for stucco, lathing and the water resistive barrier used in stucco systems. These requirements are shown in Tables 2 and 3. Both the Standard Building Code and the National Building Code provided the requirements for stucco and lathing through reference to *ASTM C925 Standard Specification for Application of Portland Cement-Based Plaster* and *ASTM C1063 Standard Specification for Installation of Lathing and Furring to Receive Interior and Exterior Portland Cement-Based Plaster.* The Uniform Building Code provided specific stucco and lath application requirements with no reference to the ASTM standards. Although the requirements in the Uniform Building Code covered many of the requirements in the ASTM standards they did not provide the same detail as was available through reference standards.

The regional codes differed on the stucco water-resistive barrier requirements, specifically the stucco water-resistive barrier over wood based sheathing. Water-resistive barriers (sometimes called weather resistant barriers) are defined in the International Building Code as “a material behind an exterior wall covering that is intended to resist liquid water that has penetrated behind the exterior covering from further intruding into the exterior wall assembly.” [ICC 2015a] Water-resistive barriers are required behind exterior claddings of frame construction buildings.

Table 2; Stucco Requirements in Legacy Codes

Code	Stucco Requirements
National Building Code (BOCA)	**SECTION 2506.0 PORTLAND CEMENT STUCCO LATHING AND PLASTERING** **2506.1 General**: All exterior and interior portland cement stucco lathing and plastering shall be done with the appropriate materials listed in Table 2505.2 and Chapter 35. **2506.2 Weather protection**: All materials shall be stored in such a manner as to protect such materials from the weather. **2506.3 Installation:** Installation of these materials shall be in compliance with ASTM C926 and ASTM C1063 listed in Chapter 35 and Section 2506.4. **2506.4 Protection after application**: At all times during application and for a period of not less than 48 hours after application of each coat, provisions shall be made to keep stucco work above 40 degrees F (4 degrees C).
Standard Building Code (SBCCI)	**1403.8 Stucco** Stucco or exterior plaster shall conform to requirements of 2504. **2504.2 Exterior Lathing and Plastering** **2504.2.1** Exterior use of Portland cement plaster shall comply with the application requirements of ASTM C926 **2504.2.2** Installation of exterior lathing and framing shall comply with ASTM C1063.
Uniform Building Code (ICBO)	**SECTION 2506. EXTERIOR LATH** **2506.1 General.** Exterior surfaces are weather-exposed surfaces as defined in Section 224. For eave overhangs required to be fire resistive, see Section 705. **2506.2 Corrosion Resistance.** All lath and lath attachments shall be of corrosion-resistant material. See Section 2501.4. **2506.3 Backing.** Backing or a lath shall provide sufficient rigidity to permit plaster application. Where lath on vertical surfaces extends between rafters or other similar projecting members, solid backing shall be installed to provide support for lath and attachments. Gypsum lath or gypsum board shall not be used, except that on horizontal supports of ceilings or roof soffits it may be used as backing for metal

	lath or wire fabric lath and cement plaster. Backing is not required under metal lath or paperbacked wire fabric lath. **2506.5 Application of Metal Plaster Bases.** The application of metal lath or wire fabric lath shall be as specified in Section 2505.3 and they shall be furred out from vertical supports or backing not less than 1/4 inch (6.4 mm) except as set forth in Table 25-B, Footnote 2. Where no external corner reinforcement is used, lath shall be furred out and carried around corners at least one support on frame construction. A minimum 0.019-inch (0.48 mm) (No. 26 galvanized sheet gage) corrosion-resistant weep screed with a minimum vertical attachment flange of 31/2 inches (89mm) shall be provided at or below the foundation plate line on all exterior stud walls. The screed shall be placed a minimum of 4 inches (102mm) above the earth or 2 inches (51 mm) above paved areas and shall be of a type that will allow trapped water to drain to the exterior of the building. The weather-resistive barrier shall lap the attachment flange, and the exterior lath shall cover and terminate on the attachment flange of the screed. **SECTION 2508. EXTERIOR PLASTER** **2508.1 General.** Plastering with cement plaster shall not be less than three coats when applied over metal lath or wire fabric lath and shall not be less than two coats when applied over masonry, concrete or gypsum backing as specified in Section 2506.3. If plaster surface is completely covered by veneer or other facing material, or is completely concealed by another wall, plaster application need be only two coats, provided the total thickness is as set forth in Table 25-F. On wood-frame or metal stud construction with an on-grade concrete floor slab system, exterior plaster shall be applied in such a manner as to cover, but not extend below, lath and paper. See Section 2506.5 for the application of paper and lath, and flashing or weep screeds. Only approved plasticity agents and approved amounts thereof may be added to portland cement. When plastic cement is used, no additional lime or plasticizers shall be added. Hydrated lime or the equivalent amount of lime putty used as a plasticizer may be added to cement plaster or cement and lime plaster in an amount not to exceed that set forth in Table 25-F. Gypsum plaster shall not be used on exterior surfaces. See Section 224. **2508.2 Base Coat Proportions.** The proportion of aggregate to cementitious materials shall be as set forth in Table 25-F. **2508.3 Base Coat Application.** The first coat shall be applied with sufficient material and pressure to fill solidly all openings in the lath. The surface shall be scored horizontally sufficiently rough to provide adequate bond to receive the second coat. The second coat shall be brought out to proper thickness, rodded and floated sufficiently rough to provide adequate bond for the finish coat. The second coat shall have no variation greater than 1/4 inch (6.4 mm) in any direction under a 5-foot (1524 mm) straight edge. **2508.4 Environmental Conditions.** Portland cement-based plaster shall not be applied to frozen base or those bases containing frost. Plaster mixes shall not contain frozen ingredients. Plaster coats shall be protected from freezing for a period of not less than 24 hours after set has occurred. **2508.5 Curing and Interval.** First and second coats of plaster shall be applied and moist cured as set forth in Table 25-F. When applied over gypsum backing as specified in Section 2506.3 or directly to unit masonry surfaces, the second coat may be applied as soon as the first coat has attained sufficient hardness. **2508.6 Alternate Method of Application.** As an alternate method of application, the second coat may be applied as soon as the first coat has attained sufficient rigidity to receive the second coat. When using this method of application, calcium aluminate cement up to 15 percent of the weight of the portland cement may be added to the mix. Curing of the first coat may be omitted and the second coat shall be cured as set forth in Table 25-F. **2508.7 Finish Coats.** Finish coats shall be proportioned and mixed in an approved manner and in accordance with Table 25-F. Cement plaster finish coats shall be applied over base coats that have been in place for the time periods set forth in Table 25-F. The third or finish coat shall be applied with sufficient material and pressure to bond to and to cover the brown coat and shall be of sufficient thickness to conceal the brown coat.

Table 3: Stucco Water-Resistive Barrier Requirements in Legacy Codes

Code	Water-Resistive Barriers
National Building Code (BOCA),	**1406.3.6 Water-resistive barrier**: A minimum of one layer of No. 15 asphalt felt, complying with ASTM D226 as listed in Chapter 35, for Type I felt, shall be attached to the sheathing with flashing as described in Section 1406.3.10, in such a manner as to provide a continuous water-resistive barrier behind the exterior wall veneer.
Standard Building Code (SBCCI)	**2303.3 Moisture** Surfaces exposed to the weather shall have an approved barrier to protect the structural frame and the interior wall covering. The barrier shall be at least Type 15 felt or kraft waterproof building paper. Building paper and felt shall be free from holes and breaks other than those created by fasteners and construction systems due to attaching of the barrier, and shall be applied over studs or sheathing of all exterior walls. Such felt or paper shall be applied horizontally with the upper layer lapped over the lower layer not less than 2 inches (51 mm). Where vertical joints occur, felt or paper shall be lapped not less than 6 inches (152mm). EXCEPTIONS: The approved barrier is not required in any of the following circumstances: … 5.Under approved paperbacked metal or wire fabric lath.
Uniform Building Code (ICBO)	**1402.1 Weather-resistive Barriers.** All weather-exposed surfaces shall have a weather-resistive barrier to protect the interior wall covering. Such barrier shall be equal to that provided for in UBC Standard 14-1 for kraft waterproof building paper or asphalt-saturated rag felt. Building paper and felt shall be free from holes and breaks other than those created by fasteners and construction system due to attaching of the building paper, and shall be applied over studs or sheathing of all exterior walls. Such felt or paper shall be applied horizontally, with the upper layer lapped over the lower layer not less than 2 inches (51 mm). Where vertical joints occur, felt or paper shall be lapped not less than 6 inches (152 mm). A weather-resistive barrier may be omitted in the following cases: … 5. Under approved paperbacked metal or wire fabric lath. **2506.4 Weather-resistive Barriers.** Weather-resistive barriers shall be installed as required in Section 1402.1 and, when applied over wood base sheathing, shall include two layers of Grade D paper.

The National Building Code required a water-resistive barrier equivalent to a single layer felt and provided no specific stucco water-resistive barrier requirement.[BOCA, 1999] Similarly, the Standard Building Code required a water-resistive barrier equivalent to a single layer of felt or paper and provided no specific stucco water-resistive barrier requirement other than the exception that an approved barrier was not required "under approved paperbacked metal or wire fabric lath."[SBCCI, 1999] The Uniform Building Code had the same basic requirements as the Standard Building Code, but had an additional requirement of the water resistive barrier "include two layers of Grade D paper" when applied over wood based sheathing. [ICBO, 1997] The purpose for equivalence to "two layers of Grade D building paper" was to prevent moisture passing through the water-resistive barrier during stucco cure, causing the wood sheathing to swell and ultimately destabilizing and cracking the stucco. [Daher, 2017] Grade D paper 2-ply products were often sold to meet this criterion and were installed with no interleafing at laps.[TSIB, 2013] This installation effectively provided a single layer water-resistive barrier with enhanced water resistance, rather than an additional drainage pathway.

The first edition of the International Building Code, introduced in 2000, was a national model code that had combined sections from the three regional codes through a public hearing process. It contained the following stucco and water-resistive barrier requirements [ICC 2000a]:

"SECTION 2510 LATHING AND FURRING FOR CEMENT PLASTER (STUCCO)
2510.1 General. *Exterior and interior cement plaster and lathing shall be done with the appropriate materials listed in Table 2507.2 and Chapter 35.*
2510.2Weather protection. *Materials shall be stored in such a manner as to protect such materials from the weather.*
2510.3 Installation. *Installation of these materials shall be in compliance with ASTM C 926 and ASTM C 1063.*
2510.4 Corrosion resistance. *Metal lath and lath attachments shall be of corrosion-resistant material.*
2510.5 Backing. *Backing or a lath shall provide sufficient rigidity to permit plaster applications.*
2510.5.1 Support of lath. *Where lath on vertical surfaces extends between rafters or other similar projecting members, solid backing shall be installed to provide support for lath and attachments.*
2510.5.2 Use of gypsum backing board.
2510.5.2.1 Use of gypsum board as a backing board. *Gypsum lath or gypsum wallboard shall not be used as a backing for cement plaster.*
Exception: *Gypsum lath or gypsum wallboard is permitted, with a weather-resistant barrier, as a backing for self-furred metal lath or self-furred wire fabric lath and cement plaster where either of the following conditions occur:*
1. On horizontal supports of ceilings or roof soffits.
2. On interior walls.
2510.5.2.2 Use of gypsum sheathing backing. *Gypsum sheathing is permitted as a backing for metal or wire fabric lath and cement plaster on walls. A weather-resistant barrier shall be provided in accordance with Section 2510.6.*
2510.5.3 Backing not required. Wire backing is not required under expanded metal lath or paperbacked wire fabric lath.
2510.6 Weather-resistant barriers. *Weather-resistant barriers shall be installed as required in Section 1404.2 and, where applied over wood-based sheathing, shall include a weather-resistant vapor-permeable barrier with a performance at least equivalent to two layers of Grade D paper.*

SECTION 2512 EXTERIOR PLASTER
2512.1 General. *Plastering with cement plaster shall not be less than three coats where applied over metal lath or wire fabric lath and not less than two coats where applied over masonry, concrete or gypsum board backing as specified in Section 2510.5. If the plaster surface is to be completely covered by veneer or other facing material, or is completely concealed by another wall, plaster application need be only two coats, provided the total thickness is as set forth in ASTM C 926.*
2512.1.1 On-grade floor slab. *On wood framed or steel stud construction with an on-grade concrete floor slab system, exterior plaster shall be applied in such a manner as to cover, but not to extend below, the lath and paper. The application of lath, paper and flashing or drip screeds shall comply with ASTM C 1063.*

> ***2512.1.2 Weep screeds.*** *A minimum 0.019-inch (0.48 mm) (No. 26 galvanized sheet gage), corrosion-resistant weep screed with a minimum vertical attachment flange of 31/2 inches (89 mm) shall be provided at or below the foundation plate line on exterior stud walls in accordance with ASTM C926. The weep screed shall be placed a minimum of 4 inches (102 mm) above the earth or 2 inches (51 mm) above paved areas and be of a type that will allow trapped water to drain to the exterior of the building. The weather-resistant barrier shall lap the attachment flange. The exterior lath shall cover and terminate on the attachment flange of the weep screed.*
>
> ***SECTION 1404 MATERIALS***
> ***1404.1 General.*** *Materials used for the construction of exterior walls shall comply with the provisions of this section. Materials not prescribed herein shall be permitted, provided that any such alternative has been approved.*
> ***1404.2 Water-resistive barrier.*** *A minimum of one layer of No.15 asphalt felt, complying with ASTM D 226 for Type 1 felt, shall be attached to the sheathing, with flashing as described in Section 1405.3, in such a manner as to provide a continuous water-resistive barrier behind the exterior wall veneer."*

The requirements for stucco and lath application reference ASTM C926 and ASTM C1063, but added more specific information and requirements. Of particular note, was the requirement for a weep screed "be of a type that will allow trapped water to drain to the exterior of the building." The requirement for a weep screed was included in the referenced ASTM C1063. So this appears to be a redundancy for emphasis. The stucco water-resistive barrier applied over wood-based sheathing is described in the singular as "a weather-resistant vapor-permeable barrier with a performance at least equivalent to two layers of Grade D paper." Additionally, that the water-resistive barrier be "vapor permeable' is specifically required. Industry information state that as vapor retarders may trap water vapor with the wall system, particularly in cold climates it is desirable to be vapor permeable in many types of construction and climates. [ACI, 1993; Melander and Isberner, 1996]

The International Residential Code (IRC), focused on one and two-family dwellings, was also introduced in 2000. In 2000, the IRC contained minimal requirements for stucco and lath application which mirrored those within the earlier UBC, and did not reference C926 or C1063 for exterior plaster. It contained no water-resistive barrier requirements specific to stucco.

No changes in stucco, lath or stucco water-resistive barrier requirements in the IBC 2003 edition. Requirements for weep screeds at the bottom of walls which mirrored those in the IBC, were added to the IRC in 2003:

> ***R703.6.2.1Weep screeds****. A minimum 0.019-inch (0.48mm) (No. 26 galvanized sheet gage), corrosion-resistant weep screed or plastic weep screed, with a minimum vertical attachment flange of 31/2 inches (89 mm) shall be provided at or below the foundation plate line on exterior stud walls in accordance with ASTM C 926. The weep screed shall be placed a minimum of 4 inches (102 mm) above the earth or 2 inches (51 mm) above paved areas and shall be of a type that will allow trapped water to drain to the exterior of the building. The weather resistant barrier shall lap*

> *the attachment flange. The exterior lath shall cover and terminate on the attachment flange of the weep screed.*

In 2006, the IBC had no substantial changes to the stucco plaster or lathing requirements, but stucco water-resistive barrier provisions began to include not only the material performance of 2-layers of Grade D paper, but also information, in the form of an exception, relating to the presence of two distinct layers. The two distinct layers of water-resistive barrier were desired because of the greater drainage that could be handled if water that intruded past the stucco was directed between the two layers.

> *"Water-resistive barriers shall be installed as required in Section 1404.2 and, where applied over wood-based sheathing, shall include a water-resistive vapor-permeable barrier with a performance at least equivalent to two layers of Grade D paper.*
>
> *Exception: Where the water-resistive barrier that is applied over wood-based sheathing has a water resistance equal to or greater than that of 60-minute Grade D paper and is separated from the stucco by an intervening, substantially nonwater-absorbing layer or drainage space."*

In 2006, the IRC began to reference ASTM C926 and ASTM C1063 and added requirements for stucco water-resistive barriers over wood-based sheathing which were the same as those in the IBC-2006.

No substantial changes were made to any of the stucco, lathing or stucco water-resistive barrier requirements of the IBC in 2009. The IRC added requirements for plaster application and curing in 2009:

> *R703.6.4 Application. Each coat shall be kept in a moist condition for at least 48 hours prior to application of the next coat.*
>
> *Exception: Applications installed in accordance with ASTM C 926.*
>
> *R703.6.5 Curing. The finish coat for two-coat cement plaster shall not be applied sooner than seven days after application of the first coat. For three-coat cement plaster, the second coat shall not be applied sooner than 48 hours after application of the first coat. The finish coat for three-coat cement plaster shall not be applied sooner than seven days after application of the second coat.*

In 2012 neither the IBC nor the IRC had changes to the stucco or lathing requirements. However, both the IBC and the IRC revised the stucco water-resistive barrier requirements to include requirements for the installing of two independent layers with the drainage directed between the layers:

> ***2510.6 Water-resistive barriers.*** *Water-resistive barriers shall be installed as required in Section 1404.2 and, where applied over wood-based sheathing, shall include a water resistive vapor-permeable barrier with a performance at least equivalent to two layers of Grade D paper. The individual layers shall be installed independently such that each layer provides a separate continuous plane and any flashing (installed in accordance with Section 1405.4) intended to drain to the water-resistive barrier is directed between the layers.*

> ***Exception:*** *Where the water-resistive barrier that is applied over wood-based sheathing has a water resistance equal to or greater than that of 60-minute Grade D paper and is separated from the stucco by an intervening, substantially nonwater-absorbing layer or drainage space.*

The 2012 revision emphasized that to realize the added benefits provided by two-layer systems, detailing must allow drainage to have a pathway out of the wall assembly and flashing that is properly integrated with the water-resistive barrier. This system also changed the requirements for installation disallowing two historical installation methods. [TSIB, 2013]

In 2015 neither the IBC nor the IRC had changes to the stucco or lathing requirements. However, the IBC updated the water-resistive barrier reference standard to *ASTM E2556 Standard Specification for Vapor Permeable Flexible Sheet Water-Resistive Barriers Intended for Mechanical Attachment*. The IRC did not have changes to its stucco water-resistive barriers in 2015.

In 2018 the IBC did not have changes to the stucco or lathing requirements, but did revise the stucco water-resistive barrier to include a new exception requiring a ventilated air space in hot-humid climates:

> *2. Where the water-resistive barrier is applied over wood-based sheathing in Climate Zone 1A, 2A or 3A, a ventilated air space shall be provided between the stucco and water-resistive barrier.*

No specification for the level of ventilation is provided. The IRC did not have any changes to the stucco water-resistive barrier requirements, but added ingredient reference standards to the stucco requirements:

> ***R703.7.2 Plaster****. Plastering with cement plaster shall be in accordance with ASTM C926. Cement materials shall be in accordance with one of the following:*
>
> *1. Masonry cement conforming to ASTM C91 Type M, S or N.*
>
> *2. Portland cement conforming to ASTM C150 Type I, II, or III.*
>
> *3. Blended hydraulic cement conforming to ASTM C595 Type IP, IS (< 70), IL, or IT (S < 70).*
>
> *4. Hydraulic cement conforming to ASTM C1157 Type GU, HE, MS, HS, or MH.*
>
> *5. Plastic (stucco) cement conforming to ASTM C1328.*

ASTM Standards C926 and C1063. Most of the specific stucco detailed requirements are defined by referenced standards ASTM C926 and ASTM C1063. The scope of *ASTM C926 Standard Specification for Application of Portland Cement-Based Plaster* is:

> *1.1 This specification covers the requirements for the application of full thickness portland cement-based plaster for exterior (stucco) and interior work. These requirements do not by default define a unit of work or assign responsibility for contractual purposes, which is the purview of a contract or contracts made between contracting entities.*

1.2 This specification sets forth tables for proportioning of various plaster mixes and plaster thickness.

Table 4 shows the development of this standard and the relevant code edition reference. The development activity has increased in the last five years. Many of the changes are clarifications to existing sections but changes also include the addition of new details and the recognition of new materials. Code references are typically two to three years behind the most recent version of the standard.

Table 4: ASTM 926 Development

Version	Year	Revisions	Code Reference
C926-98a	1998		IBC-2000; IBC-2003; IBC-2006; IRC-2006
C926-98a (2005)	2005	Reaffirmation – no change	IBC- 2009; IRC-2009
C926-06	2006	Removed reference to "plastering section" in Annex A, Section A2.3.1.3	IBC-2012; IRC-2012
C926-11	2011	Added definition of *solid plaster base;* Revisions that require correction of improper surface and accessories conditions. Added section in Annex A1 requiring accessories to be installed before plaster; Provided more detail to reference to ASTM C1063. Revised language on installation of prefabricated control joints and expansion joint members	
C926-11a	2011	Clarified when to use a furred metal plaster base and surface preparation; Added section on project documents to Appendix.	
C926-12	2012	Added definitions for *barrier wall* and *drainage wall.*	
C926-12a	2012	Revised provisions for drainage at wall/slab interface in multistory buildings.	
C926-13	2013	Added design section to Appendix; Added section on application of plaster basecoats; Clarified section thickness variation.	IBC-2015; IRC-2015
C926-13a	2013	Expansion joints added to list of naturally occurring interruptions. List already included control joints.	
C926-14	2014	Deleted section on drainage at wall/slab interface in multistory buildings.	
C926-14a	2014	Revised section on when to use a furred metal plaster base and surface preparation	
C926-15	2015	Section renumbering	
C926-15a	2015	Added reference to ASTM C578; Added definitions for *back wrap* and *polymer modified cementitious base coat*; Added sections on *Application of Field-Coated Foam Core Ornamental Features*.	
C926-15b	2015	Revised sections concerning suitable surface conditions of solid bases to receive plaster	IBC-2018; IRC-2018
C926-15be	2015	Editorial revisions	
C926-16	2016	Clarification of requirement for means of drainage at bottom of drainage wall over barrier wall; Clarification of requirement for accessories to be installed before plaster; Clarification of means of corrective action for resurfacing solid bases.	
C926-16a	2016	Added reference to C1787 and revised standard to include non-metallic plaster base.	
C926-16b	2016	Clarification of language on plaster application	

C926-16c	2016	Removed language concerning scope of "the work"; Added definition of *contract documents*; Revised scope which added a statement excluding defining contractual responsibilities;	
C926-17	2017	Revisions to sections on additions and admixtures.	

The scope of *ASTM C1063-17a Standard Specification for Installation of Lathing and Furring to Receive Interior and Exterior Portland Cement-Based Plaster* is:

> *1.1 This specification covers the minimum technical requirements for lathing and furring for the application of exterior and interior portland cement-based plaster, as in Specifications C841 or C926. These requirements do not by default define a unit of work or assign responsibility for contractual purposes, which is the purview of a contract or contracts made between contracting entities.*
>
> *1.2 Where a fire resistance rating is required for plastered assemblies and constructions, details of construction shall be in accordance with reports of fire tests of assemblies that have met the requirements of the fire rating imposed.*
>
> *1.3 Where a specific degree of sound control is required for plastered assemblies and constructions, details of construction shall be in accordance with official reports of tests conducted in recognized testing laboratories in accordance with the applicable requirements of Test Method E90.*

Table 5 shows the development of this standard and the relevant code edition references. Most of the revisions are to clarify requirements. Requirements relating to defined drainage systems were not added until this year. Code references are typically two to three years behind the most recent version of the standard.

Table 5: ASTM C1063 Development

Version	Year	Revisions	Code Reference
C1063-99	1999		IBC-2003; IRC-2003 (interior plaster only)
C1063-03	2003	No major changes	IBC-2006; IRC-2006
C1063-06	2006	The minimum weights in Table 3 for Welded and Woven Wire were revised for consistency with C933 and C1032	IBC-2009; IRC-2009
C1063-07	2007	Added Annex with requirements on gaps around wood based sheathing panels. Also updated reference specification A526 to A653.	
C1063-08	2008	Revised *Table 3 Types and Weights of Metal Plaster Bases and Corresponding Maximum Permissible Spacing of Supports.* Added Annex with requirements on expansion and control joints. Added definitions for *expansion joint* and *control joint.*	IBC-2012; IRC-2012
C1063-11a	2011	Added definitions for *barrier wall, building enclosure, drainage plane, drainage space, drainage wall*, and *water barrier system.*	
C1063-11b	2011	Added section on furring lath.	
C1063-12a	2012	Added section on framing member spacing and lath attachment. Added definition of *water barrier*.	
C1063-12c	2012	Revised sections on attachment of lath to wood framing members	IBC-2015; IRC-2015
C1063-13	2013	Clarified language on expansion joints and control joints	

C1063-14	2014	Clarified language on expansion joints and control joints	
C1063-14a	2014	Clarified language on expansion joints and control joints	
C1063-14b	2014	Added clarification on weep screed exception on water-resistive barrier placement	
C1063-14c	2014	Revised definition for *water resistive barrier*. Clarification of water resistive barrier terminology.	
C1063-14d	2014	Clarified language on expansion joints and control joints	
C1063-15	2015	Revised definition for *drainage plane*. Revised language on fastener attachment of lath.	
C1063-15a	2015	Revised definition of *water resistive barrier system.*	IBC-2018; IRC-2018
C1063-16	2016	Revised definition of *drainage wall*; Revised language on fastener attachment of lath.	
C1063-16a	2016	Revised scope which added a statement excluding defining contractual responsibilities.	
C1063-16b	2016	Added section allowing for construction adhesive attachment of accessories. Corrected table reference.	
C1063-16c	2016	Text Clarifications	
C1063-17	2017	Removed definitions of *barrier wall, drainage plane, drainage space, drainage wall,* and *water resistive barrier system*, and removed redundant section on lath attachment to framing members. Replaced terms *support* and *member* with *framing member*. Replaced terms *application* and *applied* with *installation* and *installed*. Move note on climatic and environmental conditions to new section. Added section on material selection to minimize galvanic corrosion. Added new section on staple lath attachment.	
C1063-17a	2017	Added section on defined drainage spaces over water-resistive barriers.	

CONCLUSIONS & RECOMMENDATIONS

If the timeline of stucco field concerns is compared to that of implementation of revisions to codes and standards, it is clear there is a significant lag time between building science research proposals and code revisions. A complicating factor is that that the field studies which are the basis for building science proposals are limited to specific climate regions, many of those regions being high exposure regions.

While the water management performance of stucco systems clearly depends on climate. Codes and standards have few, if any climate based requirements. Climate should be incorporated into stucco water management, specifically in drainage and ventilation drying design.

While most of the field failure surveys indicate the root cause of issues at flashings and penetrations, codes requirements often do not provide the details needed to install new, improved building practices. Although details are in the referenced standards, it appears these standards are not routinely followed.

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The in Between: Between Custom Residential + Developer Housing

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ABSTRACT

We all know architects are often perceived as exclusively accessible to the rich. Architects themselves, on the other hand, lament the lack of design thoughtfulness associated with suburban sprawl and the "cookie cutter house". But what about the in between? There seems to be a gap in architects providing design for the extremely wealthy and the demographic of the middle class family marketed to by the suburban developer. The talents of architects have even been significantly leveraged on low-income housing. In a world where everything can and should be thoughtfully designed how can architects fill the gap and provide design services on projects for modest budgets? We have a significant portfolio of single-family residential projects that accomplish this goal. Call it "custom without being custom". These projects have all been executed at less than $200/SF and provide extremely sustainable homes that employ both passive and active strategies to maximize comfort and indoor air quality. They are also beautiful - skillfully crafted to meet the specific needs of our clients and the particular aspects of their homes site.

Introduction / The Case for "The In Between"

Residential construction is often architect-less or at the very least an architect has created a "cookie cutter" solution which is replicated over and over again with little concern for the particular aspects of place or the needs of a specific client. Why? Is it because architects are too expensive? Is it because potential clients see architects as inaccessible for this reason? We would suggest it can be either or both. Architects are, in many ways, exclusively a commodity of the wealthy. And architects are often prone to pretension which feeds this exclusivity both outwardly and inwardly. Fortunately, for reasons we won't go into here, architects typically have a potent sense of altruism so their skills are often leveraged for the poor in the form of low income housing and other civic/cultural/non-profit projects. And while it is easy to validate the architects relevance to both of these demographics, with respect to economics and/or social consciousness, there is a vast swath of the population which lies within what we will call "the in between" for the purposes of this paper.

Ironically, architects often spend a considerable amount of their emotional capital lamenting the lack of design apparent with residential construction occurring in this in between. The “cookie cutter” or “McMansion” developments often take the brunt of architects derision because they lack design cohesion and devalue the architect in the eyes of the middle-class for whom these typologies are marketed. Sure there is a constantly expanding set of prefab/kit options available which increase design quality and improve sustainability, but these do not address the truly custom. Just as suburban sprawl developer led housing offer various “options” these prefab options are also preselected from a kit of parts with a limited number of variations. They do not allow the client to collaborate with an architect directly in a way that results in a singular/unique home. For the purposes of this paper we will focus on this lack of accessibility which is only addressed if architects can make themselves useful directly to an individual home owner.

So what if architects took on the challenge of truly addressing this gap? There are challenges for sure, on all sides, but it is possible and ultimately very rewarding.

Challenges

When considering the challenges associated with designing single family residential projects for an individual home owner the first place to look is economics. Design fees are always the first cost thought to be expendable. Unfortunately, the smaller the project the higher the design fee as a percentage of the construction cost. This is often a deal breaker for clients. It is difficult for clients to understand the value they receive in return when they invest in an architect. They see the (approximately) 10-20% in design fees as a direct reduction in the money they can spend on the house itself. Unfortunately, what clients don’t realize is the buried costs they incur when they buy directly from a builder. Studies have shown they can pay as much as 40% more than the actual construction value (materials and labor) while not benefitting from the process of customizing their home to their specific needs. This lack of transparency often results in cheaper materials and cheaper execution. A critical roll of the architect is to manage the construction process on behalf of the client to make sure material quality and craftsmanship are maintained.

In order to manage our fees we typically execute smaller projects under time and material contracts. This allows us to set the clients expectations up front and empower them to understand the implications of their requests for revisions/changes and to participate in the management of fee expenditure. This doesn’t always lessen overall fee expenditure, but it certainly provides a level of transparency which allows the client to understand the value of their architects time.

Another aspect of economics which is a challenge for custom architecture is the need to manage the contractors risk up front. Many of the contractors we encounter when servicing clients within "the in between" are often inexperienced with architects and are inclined to buffet the risk they foresee by burying it in their construction costs. In these cases we see it as our responsibility to bridge the gap and help them understand the details and material systems completely before their final price is determined. Over the course of a number of such projects we've developed a consistent methodology which mitigates these risks for the contractor and reduces costs to the home owner.

Consistent Methods / "The Lowes Special"

Our consistent methodology for designing beautiful single family homes at modest budgets begins with a set of choices. Every decision is weighed on the basis of design/beauty, function, economic impact and last but not least sustainability.

The first decision is always the same. We choose simplicity. Not that simplicity is inherently cheaper, because often creating simplicity (think minimalism) requires more precision. First, we endeavor to simplify the form. We focus on one critical move in the project. At Courtyard House in Springfield, VA we separated a master suite addition from the existing house across an outdoor courtyard.

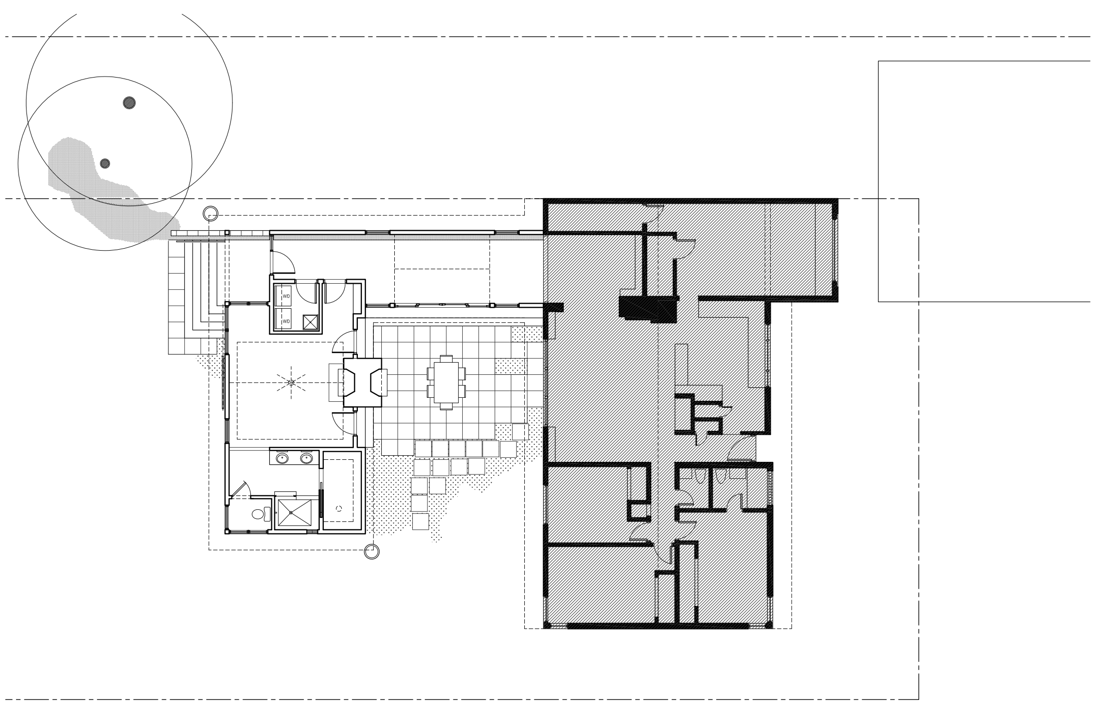

Figure 1. Floor plan - Courtyard House

Figure 2. View of courtyard from roof - Courtyard House

This played to the couples appreciation for the courtyard tradition of the American southwest, particularly New Mexico. At the same time, because we'd created a design requiring the construction of significantly more exterior surface area (cladding) it required us to make other concessions later in the design process to reduce cost. One such decision was to cover the roof of the addition with asphalt shingles matching that of the original structure. Under other circumstances we would almost certainly have specified a more significant roof (i.e. metal). However, the result is the house reading as a unified whole and actually improves the final product. Often wrestling with the perceived limits (obstructions) sets up the creative response.

Simultaneously, we reduce the number of variations, which in turn reduces the sheer quantity of details. Typically, the less details you ask a contractor to execute the less cost both in terms of construction hours, but also the quantity of design drawings required (less fee). That isn't to say we don't make a significant move or that we don't design beautiful details which require care when assembling.

One such area where we consistently employ rigorous detailing is in exterior cladding. This is a place where we often ask contractors to expand their comfort zone. We often choose non-traditional materials for this application, but endeavor to select easily accessible and economical ones. When using non-traditional cladding materials we take care to detail the assembly in a simple way. Conversely, if we employ a more traditional cladding, such as wood siding, we will ask the contractor to assemble it in a more contemporary way - perhaps as a self ventilating rain screen with expectations for precision corners (mitered) and trim.

An example of both of these approaches can be seen at Ridge House in Berkeley Springs, West Virginia. Here we clad portions of the house with a typical standing seam metal roof, but transition the material seamlessly from roofing to siding which creates the sense of the form being folded. While the form looks somewhat radical the assembly utilizes exposed fasteners direct applied to the exterior sheathing making the install uncomplicated. Additionally, the standing seam metal is extremely economical, is readily available off-the-shelf (almost no lead time) and does not require intensive shop drawings (reducing fee for review of those). The locally sourced hemlock is detailed as a rain-screen. Each window opening is thoughtfully trimmed and the outside corners are interlocked taking a traditional material and making it appear rather contemporary.

Figure 3. Intersecting volumes - Ridge House

Another project example which shows both cladding strategies is found at Taphouse in the Canton neighborhood of Baltimore, Maryland. Abstractly, the house responds directly to the typical masonry row house volume with regular punched openings.

Often, within this context, the storefronts and trim will be painted black. Our strategy for renovating and adding to an existing pre-Civil War conglomeration of structures was to peal away much of the deteriorated exterior cladding. What we put back are two simple geometric, almost plutonic, volumes. One of these volumes, the existing structure which remained, is clad in traditional masonry wall construction (effectively brick applied as a rain screen over wood frame construction). Here traditional masonry detail is employed which directly reflects local tradition. The second volume, on the other hand, is rendered in a much more contemporary way yet still utilizes wood siding. The almost black heated treated ash cube mirrors the black trim of adjacent structures but emphasizes the newness of the structure as it appears to hover over an exterior courtyard. The rain screen detailing here is significantly more technical, as the tongue and groove wood planks are connected back to the sheathing using a pre-engineered rain screen clip. Although the wood is certainly modeled due to the grain of the material, the systems precision and the mitered corners effectively cast the cubic volume as a pure geometry which is quite striking within this emerging neighborhood.

Figures 4 + 5. Taphouse

In both of these examples one of the typically most costly aspects of construction, residential or otherwise, is sourced economically from suppliers who are familiar to most residential contractors. This aspect is unsurprisingly the window package. The entire window package at Ridge House (Plygem), including a fifteen foot sliding door, was procured from Lowes. Our contractor, Joe Braun from No Worries

Carpentry in Great Cacapon, West Virginia, was extremely energetic, talented as a carpenter, and eager to cut his teeth on an architecturally sophisticated structure, but was used to sourcing all of his building materials from Lowes. Therefore, we made a concerted effort to specify things available from there in order to reduce the overall cost of the house and mitigate his assumed risk. The windows at Taphouse are Eagle Windows (E-Series) from the Andersen Architectural Collection. This allowed us to execute a clean and modern aesthetic using repetitive casements and similarly large sliders without paying a premium through more expensive suppliers. In both examples the windows are non-custom and selected as typical off-the-shelf sizes.

Figure 6. Courtyard as viewed from the garage - Taphouse

Another aspect of residential design and construction which can result in considerable costs is interior finishing. While the structure and exterior envelope typically comprise the vast majority of the overall cost of a home, the interior finishes are often where clients spend most of their energy. When budgets are tight this requires the architect manage their expectations and make an effort to maximize expenditures. In the case of Ridge House, where the budget was less than $170/SF, there are essentially no “finishes”. The walls are painted drywall with 1x pine trim throughout. and the floors are simply an exposed concrete slab with a clear sealer applied post-curing. In this particular case the raw aesthetic spoke to our client who is an accomplished artist. Perhaps more importantly, we focused the occupants attention on the surrounding landscape making nature the house’s primary “finish”. This was accomplished either by using significant portions of glazing to blur the distinction between inside and outside (16’-0” wide slider between the Living Room and Porch) or by the deliberate location of smaller punched openings (windows) which focuses ones view from a specific space or position in the house to a specific element in the landscape.

Figure 6. Living Room and Porch - Ridge House

Figure 7 + 8. Kitchen - Ridge House + Highland House

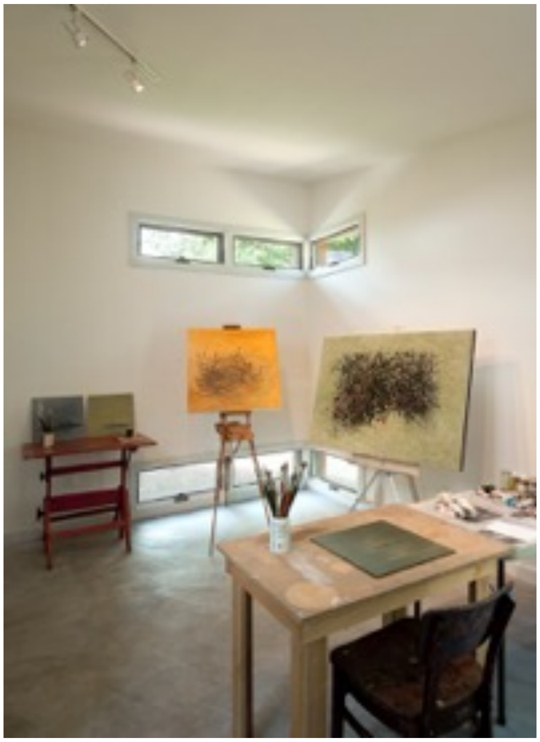 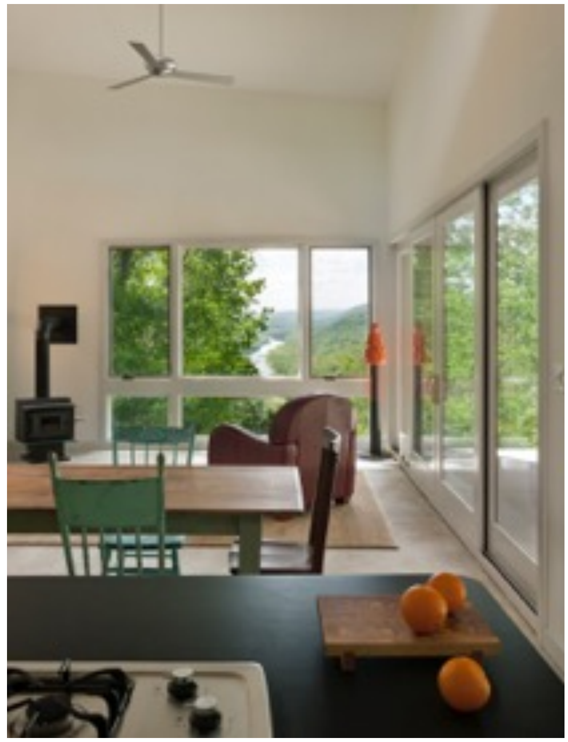

Figure 9 + 10. Painting Studio and Kitchen/Dining/Living - Ridge House

"Finishes" tend to mount in spaces requiring considerable infrastructure, i.e. kitchens and bathrooms. As far as kitchens go, one could easily spend something close to the entire cost to construct Ridge House or one could spend considerably less. In our effort to serve "the in between" we have achieved both economy and an appropriately contemporary aesthetic using solutions from IKEA Both at Ridge House and Highland House, a dramatic renovation of a small cabin in Upper Tract, West Virginia we designed and sourced complete kitchens, including appliances, from IKEA for less than $10,000.

Passive Sustainability / Whether They Ask For "It" or Not

In a world where our response to sustainability is paramount, particularly with regard to the built environment, we do not leave those results up to the predilections of our clients. While we recognize some sustainable strategies require considerable investment there are other aspects which can be accomplished as a matter of course.

Our initial focus is on passive strategies, beginning with considering the orientation of the house on a given site. This is true with rural settings where we have control over the actual location and orientation, but also with urban sites or renovations where we may have to exercise more subtlety in response to heat gain and natural ventilation.

Figure 11 + 12. Liquid applied air barrier and Zip Sheathing - Taphouse + Spa Creek

Regardless of specific site conditions we spend considerable time on the exterior wall assembly. This is one aspect of construction where we advise our clients to avoid compromise. Our focus is on creating a tightly sealed and highly insulated envelope regardless of the cladding material. For insulation we typically utilize closed-cell spray foam or a hybrid between spray foam and out-sulation (often rigid polystyrene with taped joints). When budgets allow, our preference for sealing the wall against air and moisture infiltration is to use a liquid applied system (Taphouse), however should there be fiscal constraint, we will employ a product such as Zip System by Huber Engineered Woods. This product simultaneously acts as the envelopes insulation, exterior sheathing to which the cladding is fastened, and the air and water barrier. In most cases finding solutions as multifaceted as this will result in optimized economics. A recent example of this application is Spa Creek House in Annapolis, Maryland.

Efficiency is another passive strategy towards increasing the sustainability of a home. When programming and planning the design of a house we focus a great deal on the versatility and flexibility of spaces. This often results in an open plan, which is the hallmark of a modern aesthetic. The ideal is to be able to do more with less. We also consider the volume, allowing spaces which require lower ceilings to exist within a shallower volume and those which require higher ceilings to achieve those as well. This strategy can have a positive effect on both material quantities, reducing them and the long term costs associated with cooling and/or heating less overall volume.

Ridge House exemplifies this strategy of efficiency both in terms of the plan and massing. The plan is extremely efficient allocating almost no space for “corridors” while overlapping the living, dining and kitchen program into a single space. This space is located within a higher volume, whereas the rest of the program (bedroom, painting studio, etc.) reside in a much more modest volume.

Figure 13. Living, dining and kitchen volume rising above - Ridge House

Highland House represents an example of this strategy applied to a renovation with an extremely modest budget (less than $100,000). In this case we created more openness and functionality without expanding the footprint. This was achieved by removing a small bunk room which was obstructing the rest of the living spaces. The bunk room program was moved into a new loft over the bathroom which was made possible by the singular design move, removing the original shed roof and elevating it onto four new columns. These discreet, yet effective moves, result in a newly unified Great Room that blends form and function, providing a greater delineating between living and sleeping while simultaneously creating a lofty, open space that connects to the majestic Appalachian landscape surrounding the cabin.

Another passive strategy which both Ridge House and Highland House share is made possible through the utilization of more than one of the previously described concepts. Combing the allowance of larger volumes over the living spaces with the need to create deep overhangs to shade expanses of glass both homes employ clerestory windows. These clerestory windows serve two critical purposes: the first is that they draw in significant amounts of ambient light which dramatically reduces the use of electric light throughout the day, and the second is that when open they introduce stack effect ventilation, drawing hot air up and out of the space.

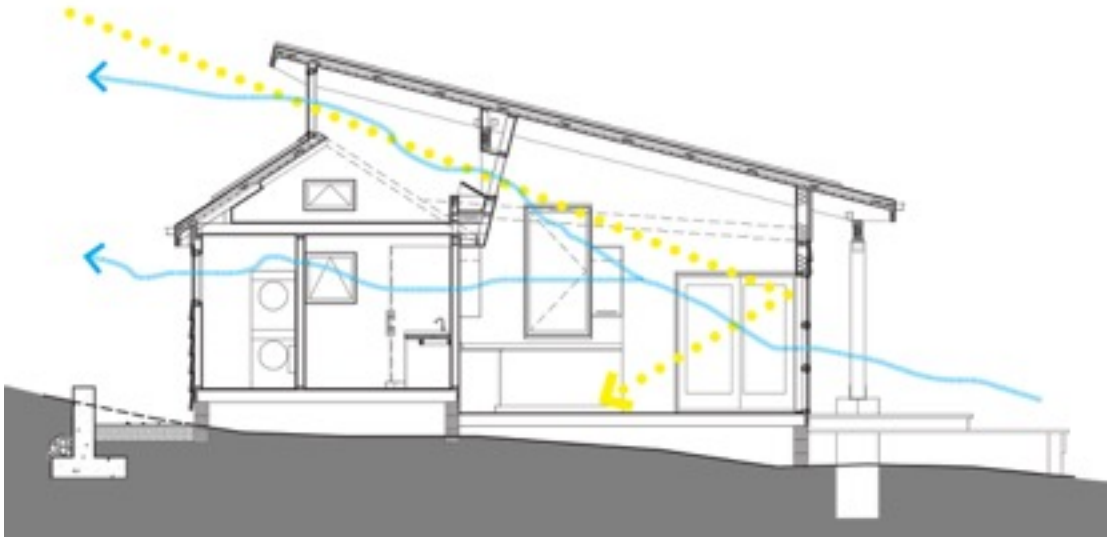

Figure 14. Section through Loft and clerestory windows - Highland House

Active Sustainability / Effectiveness + Economics

Achieving a project, conscientious to the ideals of sustainability, as has been shown above, is simply based on the wherewithal to strategize for these solutions from the outset. Simply by employing passive design strategies of the project, the investment burden pales in cost, when juxtaposed to the expenditures of active sustainable strategies such photovoltaics, high-performance heating and cooling, etc. While these systems certainly have a "sex appeal" in the overall "green" movement, they often are challenged by lengthy pay-backs and subsidization, adversely impacting the perceived value when scrutinized under the auspices of life-cycle analysis.

Passive strategies are not immune to the burden of cost either. Choices in insulation, glazing, and other sustainably oriented products often come with a premium too. However, when these choices are pitted against those systems reliant on active, electronic, technological, and machine based systems (often obsolete shortly after they come to market), we remain steadfast to the "analogue."

While by no means are we unsupportive of active systems, we do approach these systems with a prudent caution, employing them where we believe our clients dollar - in the long run - will go the farthest. On our "In Between" projects we focus primarily on a number of elements which increase energy efficiency and the health of a building at relatively low costs, where the benefit is substantial enough to warrant the cost. Three examples, which we recommend on most of these projects, are the incorporation of an energy recovery ventilator (ERV), some form of radiant heating (whether hydronic or electric and whether in-floor or wall mounted panels), and split systems for cooling.

ERV's are an extremely valuable and relatively low cost solution for both the introduction of fresh air into a house and the reduction of energy use during both cold and warm seasons by exchanging energy from the discharged air back to the incoming air (effectively precondition it). Both Ridge House and Taphouse utilize an ERV. In the case of Taphouse it is slightly more sophisticated as there are ERV's on both sides of the building, and on multiple levels, which are programmed to speak to one another, modulating the ventilation and recovery of air and energy across the entire three level house.

Radiant heat is often preferable to forced air systems due to the overall energy efficiency of hydronic systems, when employed as either an in-floor system or wall mounted panels. In-floor systems can be both hydronic and electric and the electric systems have continued to dramatically increase in terms of performance while simultaneously becoming more economical. The entire concrete slab-on-grade at Ridge House has a hydronic radiant system and Taphouse employs both an in-floor electric system as well as radiant panels. At Taphouse the electric in-floor system is the Ditra-Heat system by Schluter Systems which is ideal for incorporation in spaces with tile floors such as bathrooms.

The final element of an economical and efficient residential HVAC system is the split system air conditioning unit. The advantages of a split system are that is eliminates the need for a large air handling unit since it relies on the ERV for the introduction of fresh air into the space and cools the air at the point of use. Split systems require relatively small outdoor condensers and can be ducted to feed multiple spaces. They can also be specified as wall mounted or ceiling integrated allowing flexibility in terms of how they are located throughout the house.

Figure 15. Sustainable strategies diagram - Taphouse

Figure 16 + 17. Exterior views with ERV's visible - Taphouse

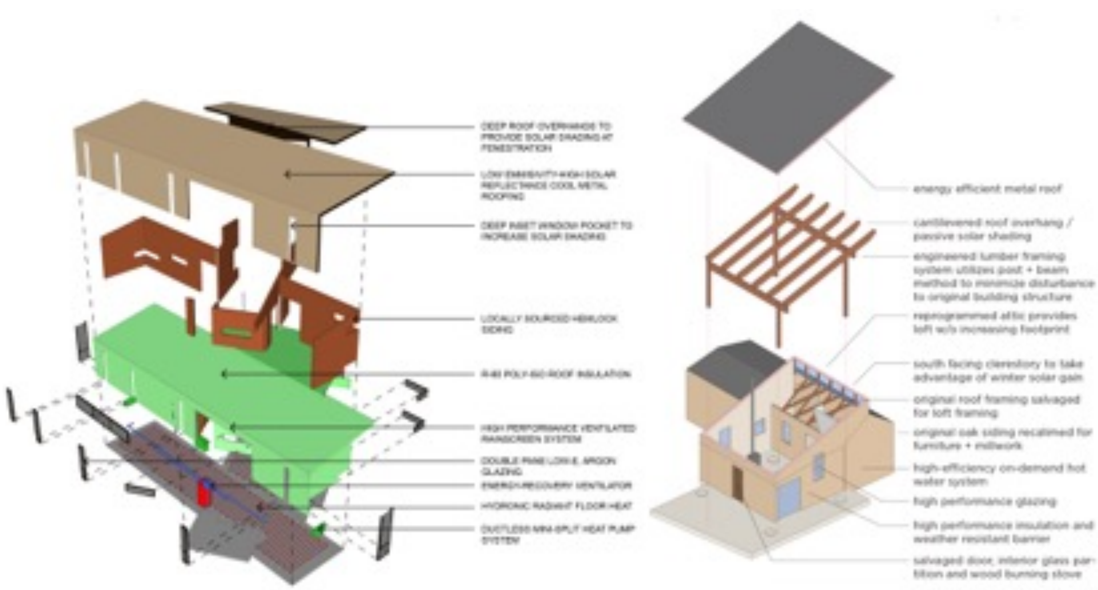

Figure 18 + 19. Sustainable strategies diagrams - Ridge House + Highland House

Conclusions / Filling the Gap

Good design is a commodity, but more than that it is a necessity. Good design does not, and should not mean solely aesthetic beauty. Instead it should also mean beauty in terms of the protection of the health, safety and welfare of the user. These are in fact tenets of an architects creed.

Unfortunately, the commodity of architecture is often utilized solely by the rich. In residential construction, this is due to the expectation that architects (their fees) and the things they design are exclusive (i.e. too expensive). While this can often be the case, it is not always and certainly should not exclude the middle class from achieving the dream of a custom home. Many talented and capable architects are willing to develop fee structures which support a clients interests in valuing the overall economics while also protecting their own interests relative to the expenditure of time and their creative capital (which is the commodity).

The multiple examples presented here are beautiful homes which fill this gap between housing for the ultra-rich and low income housing. The solutions to achieve this architecture for “the in between” cover aspects of sustainability, constructibility, material systems specification and project management. All of these aspects are critical to the success of each project and must work in concert for such a project to be realized.

IRC and IBC Provisional Requirements for Different Scale Residential Building Projects

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Abstract

Residential construction projects can vary vastly in size from single-family homes to vast residential high-rise towers and everything in-between. Due to this residential scale in the building industry, the governing building codes and standards for residential construction are complex and spread across multiple documents. On the small size, designs are governed by the IRC while large projects are governed by the IBC. Specific wording within IBC mandates special requirements for large projects that are used for residential applications thus making the code more cumbersome to navigate through. To clarify design requirements, this paper will discuss a comparison of provisions through guidelines between the IBC and IRC in relationship to other relevant codes and standards. Details will focus on the differences, limitations, and general processes necessary to ensure different residential projects meet all design code requirements. The results will give designers and builders a better understanding of the complexity of code provisions and prevailing factors that influence and scope the design through clarifying code intent.

Introduction

Residential construction projects can vary vastly in size from single family homes to vast residential high-rise towers and everything in-between. Structures and buildings that consist of and include residential portions where humans reside encompass the widest range of occupants. People in these buildings include infants up to and including the elderly. Because of this, residential projects are more susceptible to the careless acts (intentional and not) of the occupants. As a result, consequences of exposure to the effects of fire are the most serious threat to human life and safety in these projects. Particularly coupled with traditional building materials that most residential projects utilize.

The value of new construction of residences in the early 2000's was 2.4% of the Gross Domestic Product (GDP) (U.S. Census 2001) and all residential homes (new and retrofit) accounted for about 5.3% of the GDP. These values indicate the importance of generating design solutions that will have impact. Wood-framed wall construction is the most prevalent construction type applied in single-family dwellings (Obiso 1997). Buildings account for 37% of the total primary energy use in the U.S., compared to 37% for industry and 26% for transportation (Diamond 2001). Ahrens (2007) records

"NFPA estimates that U.S. fire departments responded to an average of 375,200 reported home structure fires per year during the five-year-period of 2000-2004". These fires caused an estimated average of 2,970 civilian deaths, 14,390 civilian injuries, and $5.6 billion in direct property damage per year.

Due to the residential scope in the building industry, the governing building codes and standards for residential design construction are complex and spread across multiple documents. On the small side, designs are governed by the International Residential Code (IRC) while larger projects are governed by the International Building Code (IBC). Specific wording within IBC mandates special requirements for large projects that are used for residential applications thus making the code more cumbersome to navigate through. This paper focuses on clarifying the understanding of the primary provisions to classify the type of residential, the permitted uses if they are permitted to be mixed, and governing criteria on the overall size of the residential projects.

Overview of IBC and IRC

To design residential buildings, various codes and specifications designers must be taken into account. To design a residential structure, the design professional must be familiar with the following codes and design standards:

- International Residential Code (IRC) (ICC 2015b)
- International Building Code (IBC) (ICC 2015a)

Both the IRC and IBC have unique sets of design-related information. It is important that designers use the latest editions of these documents because they are continually updated with new design information based on ongoing research. The building codes give Building Officials the authority to approve alternate materials, designs and methods of construction that comply with the intent of the provisions of the codes and are at least the equivalent to those prescribed in the code.

The IRC (ICC 2015a) is deemed a prescriptive code for one- and two-family dwellings with no more than three stories. It also applies to townhouses with no more than three units. The IRC applies to the large majority of residential construction in the United States. The IRC provides extensive prescriptive design information in the form of tables and figures. The IBC (ICC 2015b) is essentially an engineered design code, although several prescriptive tables are in the document. The IBC is used when the residence exceeds the scope of the IRC.

Scope / Project Scale for Residential in the IBC vs IRC

The IRC was created to serve as a complete and comprehensive code that regulates the construction of single-family houses, two-family houses (duplexes) and buildings that are three or more townhouse units. All buildings within the scope of the IRC are limited to a maximum of three stories above grade plane. Anything outside of this domain automatically defaults to the IBC. For example, a four-story single-family house would fall within IBC not the IRC. The ICC devotes a separate building code to residential construction so that residential designers not need to navigate through a multitude of code provisions that do not apply to residential construction within the IBC. By doing this it further allows for residential and nonresidential code provisions to be distinct and tailored to the structures that fall within the appropriate code's scopes.

Unlike the IBC, the IRC contains coverage for all components of a house or townhouse, including structural components, fireplaces and chimneys, thermal insulation, mechanical systems, fuel gas systems, plumbing systems and electrical systems. In other words, the IRC is meant to be all inclusive for typical residential construction project, it relies on other codes only where alternatives are desired or where the code lacks coverage for the uncommon aspect of residential construction.

Prescriptive vs Performance Provisions in Residential Codes

The IRC is a prescriptive-oriented code with some examples of performance code language within the body of the document that permit performance alternatives. If we look at IRC Section R301.1 for example, is written in performance language, but states that the prescriptive requirements of the code will achieve such performance. As such, designers feel like the IRC is more of a comprehensive “cookbook” of what to do to have an occupied residential project (that meets IRC limitations) (ICC 2015a). It is important to understand that the IRC contains coverage for what is conventional and common in residential construction practice. While the IRC will provide all of the needed coverage for most residential construction, it might not address construction practices and systems that are atypical or rarely encountered in the industry. Sections such as R301.1.3, R322.1, M1301.1, and P2601.1 refer to other codes either as an alternative to the provisions of the IRC or where the IRC lacks coverage for a particular type of structure, design, system, appliance or method of construction (ICC 2015a).

The IBC is a mixture of prescriptive-oriented code and performance-oriented code language within the body of the document. Beside the scope difference between the IRC and IBC, the provisions within the IBC are more overarching and are in many situations more open to multiple solutions. Many of the sections intent is to lay the group work for the scope but permit the design professionals to engineer the systems. As such, to design and build residential building that falls within the IBC takes a greater skill and education level than what the IRC would need, due to the substantial prescriptive nature.

When a building that is not designed as a conventional construction contains structural elements exceeding the limits the IRC, these elements must be designed using accepted engineering practice. The extent of these designs only need to demonstrate compliance of nonconventional elements with other applicable provisions and are be compatible with the performance of the conventional framed system. Engineered design in accordance with the IBC is permitted for all buildings included in the scope of the IRC.

Basis of Occupancy for Residential

Use and Occupancy are fundamental to a building for it defines the occupants and how the building will be used. To understand the code requirements for residential, we must understand Use and Occupancy classifications as these two items drive the other code requirements. Potential uses for a building are assigned an occupancy classification based on the specific occupant and content hazards that are anticipated to exist. This is true for residential. Uses having similar hazard characteristics are all grouped into the same occupancy classification. Proper occupancy classification is a major factor in achieving the code's intended purpose of establishing a *"minimum requirements to provide a reasonable level of safety, public health, and general welfare" IBC 2015 §101.3.*

According to the provisions of §302.1 of IBC 2015, there are 10 main classes of uses where some uses have several subclasses (ICC 2015b). Unlike building construction types, there can be multiple uses in a single building. Table 1 shows all of the different classes. It can be seen in Table 1 that residential has its own group and subsets that are defined in §310.

Table 1: Use Classifications in the IBC

Group Type	Sub-Type	Code Section
Assembly	A-1 to A-5	303
Business	B	304
Educational	E	305
Factory / Industrial	F-1 to F-2	306
High Hazard	H-1 to H-5	307
Institutional	I-1 to I-4	308
Mercantile	M	309
Residential	R-1 to R-4	310
Storage	S-1 to S-2	311
Utility and Misc.	U	312

The residential group in the IBC includes buildings for sleeping purposes when classified as group R and when not regulated by the IRC or other groups in the IBC. There are 4 subgroups to residential, R-1 through R-4. Generically the way that the IBC groups building or part of a building is considered to be a residential occupancy if it is intended to be used for sleeping accommodations (including assisted living facilities) and is not an institutional occupancy. Now, institutional occupancies are similar to residential occupancies in many ways. However, they differ from each other in that institutional occupants are in a supervised environment or are under some form of restraint or physical limitation that makes them incapable of complete self-preservation

(ICC 2015c). The number of these occupants who are under supervision or are incapable of self-preservation is one distinguishing factor for being classified as an institutional or residential occupancy.

For each subgroup there are requirements within the code that are common to the main classification where there further exists requirements for each specific subset. The common requirements are applicable are mandated for all types unless exceptions are made in subset provisions. For example, the automatic sprinkler system requirements apply to each subset for the R Group.

R-1 are sleeping buildings that are primarily transient in nature. These types of occupancies include: Boarding houses, congregate living facilities, Hotels and Motels. These are grouped together based on that the occupants are not as familiar with the building as those residents in non-transient facilities such as apartment buildings and single-family dwellings.

R-2 are sleeping buildings that are primarily permanent in nature with sleeping and dwelling units. Group R-2 occupancies have occupants that are primarily permanent in nature, including (ICC 2015c): Apartment houses, Boarding houses and Congregate living facilities with more than 16, Convents, Dormitories, Fraternities and sororities, and vacation timeshare properties. The main difference between R-1 and R-2 is the duration of stay. If less than 30 day stay then it is an R-1. In most cases individual dwelling units in Group R-2 are either rented by tenants or owned by the occupants. The code does not make a distinction between either type of tenancy. Residential condominiums are treated in the code the same as Group R-2 apartments.

R-3 building are residential buildings with occupants are primarily permanent in nature and are not classified as the other R Groups or I Groups (ICC 2015b). Examples of these include but are not limited to: buildings that do not contain more than two dwelling units, boarding houses that are non-transient in nature with 16 or fewer occupants or those that are transient in nature with 10 or fewer occupants, care facilities that provide accommodations for five or fewer persons, congregate living facilities that are non-transient with 16 or fewer occupants or transient ones with 10 or fewer, and lastly lodging houses with five or fewer guest rooms.

Furthermore, group R-3 buildings include all detached one- and two-family dwellings and multiple (three or more) single-family dwellings (townhouses) more than three stories in height. These same buildings that are under three stories or less are not classified as Group R-3 per the IBC. Instead, they are regulated by the IRC. In addition to the story height, the IBC further requires that each pair of dwelling units in multiple single-family dwellings greater than three stories in height must be separated by fire walls or by two exterior walls (ICC 2015c). Duplexes, buildings with two dwelling units, must be detached from other structures in order to be regulated by the IRC. A duplex attached to another duplex would be required to comply with the IBC and be classified as Group R-2 or R-3, depending on the presence of fire walls.

R-4 are residential buildings that include residential care and assisted living facilities typically with 6 to 16 clients. There are two further conditions. Condition 1 is where all occupants are capable of responding to an emergency without assistance, and Condition 2 is where limited assistance may be necessary for any single occupant (ICC 2015c). This group includes, but is not be limited to, the following: alcohol and drug centers, assisted living facilities, congregate care facilities, group homes, halfway houses, residential board and care facilities, and social rehabilitation facilities.

Residential occupancies represent some of the highest fire safety risks of any of the occupancies. Because of the relatively high fire risk and potential for loss of life in buildings in the event of a disaster, the code has stringent provisions for the protection of life in R-1 and R-2 occupancies. R-3 occupancies, however, are not generally considered to be in the same domain of risk to human life loss according to the intent of the IBC. As such, R-3's are not subject to the same level of regulatory control and are reflected in the provisions.

Basis of Use Classification for Residential

While a building is classified by uses and can be classified generically a residential, according to the IBC, a building can have several different types of occupancy. The occupancy classification is typically established by the design professional. This typically done early in design development. Where there is disagreement, it is the building official's responsibility to make the final decision however this is appealable should the owner and designers disagree. Designers should be asking themselves as they go about classifying a project: 1) what are the individual occupancy types that are in the building? and 2) what is the relative size of the individual occupancies? These two questions can significantly impact the classification and as a result, the permitted occupancy group classification for R. Based on their answers, designers can select from the following use classifications. They include:

- Single occupancy
- Occupancy that changes at different times of the day.
- Multiple occupancies at the same time (mixed use).
    - Separated
    - Non-separated
- subservient space to the primary use that do not affect the overall classification of the space:
    - Incidental occupancy
    - Accessory occupancy

Single occupancy is the simplest of classifications, as the building has only one use associated to it. Size of the building has no bearing in that the code is all based on use. The building could be very small or large. Only a very small % of the buildings built are solely a single use structure. Most buildings have the need for secondary uses to serve the primary use. These secondary uses are considered incidental and accessory occupancies, both of which are rarely residential type uses. If the amount of smaller use area as a percentage of the building is small (10% of total), then the relative risk is small and doesn't impact the bigger risk.

In the cases where more than one occupancy in a single building is needed, then this can be accommodated by: non-separated occupancies or separated occupancies (ICC 2015b). For ease of classification and design, the architect, owner, and/or engineers may want to assume a building to be a single occupancy structure even when multiple occupancies are present. In this case the most hazardous occupancy is used as the occupancy for the entire structure.

In mixed-use buildings that contain R Group occupancies they are primarily R-1 in nature due to the classification and the robust nature of R-1 (ICC 2015c). Other common occupancies are often found in buildings with R-1 include: nightclubs (Group A-2), restaurants (Group A-2), gift shops (Group M), business offices (Group B), health clubs (Group A-3) and storage facilities (Group S-1). Another common set of mixed use residential is with R-2 Group. Specifically R-2 buildings that are primarily dormitories. They further include in them: cafeterias or dining rooms (Group A-2), recreation rooms (Group A-3), offices (Group B) and study and meeting rooms (Group A-3).

According to the IBC, a room or space that is intended to be occupied at different times for different purposes shall comply with all of the requirements that are applicable to each of the purposes for which the room or space will be occupied (ICC 2015c). To achieve this the strictest requirements for each use must be met. Now in order to be classified to be a as a separated space the IBC requires that fire separation walls/barriers be established. Table 508.4 in the IBC states the (Figure 1) hrs. for requirements (ICC 2015b). As noted here, the barrier requirements are different if the building is sprinklered (S) or not sprinklered (NS). The basis of this is property conservation with the added benefit of occupant protection.

OCCUPANCY	A, E		I-1[a], I-3, I-4		I-2		R[a]		F-2, S-2[b], U		B[e], F-1, M, S-1		H-1		H-2		H-3, H-4		H-5	
	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS	S	NS
A, E	N	N	1	2	2	NP	1	2	N	1	1	2	NP	NP	3	4	2	3	2	NP
I-1[a], I-3, I-4	—	—	N	N	2	NP	1	NP	1	2	1	2	NP	NP	3	NP	2	NP	2	NP
I-2	—	—	—	—	N	N	2	NP	2	NP	2	NP	NP	NP	3	NP	2	NP	2	NP
R[a]	—	—	—	—	—	—	N	N	1[c]	2[c]	1	2	NP	NP	3	NP	2	NP	2	NP
F-2, S-2[b], U	—	—	—	—	—	—	—	—	N	N	1	2	NP	NP	3	4	2	3	2	NP
B[e], F-1, M, S-1	—	—	—	—	—	—	—	—	—	—	N	N	NP	NP	2	3	1	2	1	NP
H-1	—	—	—	—	—	—	—	—	—	—	—	—	N	NP	NP	NP	NP	NP	NP	NP
H-2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	N	NP	1	NP	1	NP
H-3, H-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1[d]	NP	1	NP
H-5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	N	NP

Figure 1: Occupancy separation requirements.

Specifically related to residential, you cannot mix the following with residential: H-1 and H-2 through H-5 NS option along with I-1 through I-4. This is due to the hazard level associated with each H sub category. The rest have an hourly rating or for residential by other residential require no separation.

Building Height, Area, and Number of Story Restrictions for Residential

The IBC regulates building height, area, and the number of stories to limit the magnitude of a fire that may potentially develop. By limiting floor-area we limit: the number of occupants in the building, the fire load and fire size and property damage. By imposing height restrictions, we limit: the number of occupants in the building, address egress concerns and fire department access limitations, the time required for the evacuation of the occupants increases, and lastly, the potential for structural collapse. When going through the iterative design process, there are two ways which we can look at Height and Area to establish if the IBC is satisfied: Analysis after a design generation (Figure 2) or as part of design (Figure 3). For either design or analysis, we need to know if the building will be:

- Single use
- Mixed non-separated
- Mixed separated

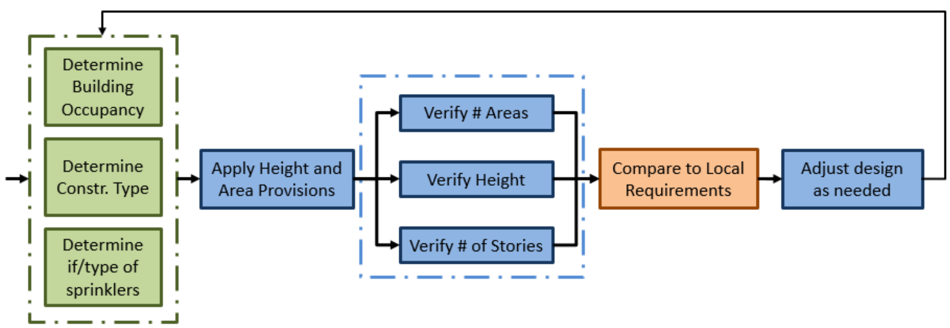

Figure 2: Process for analysis after a design is generated

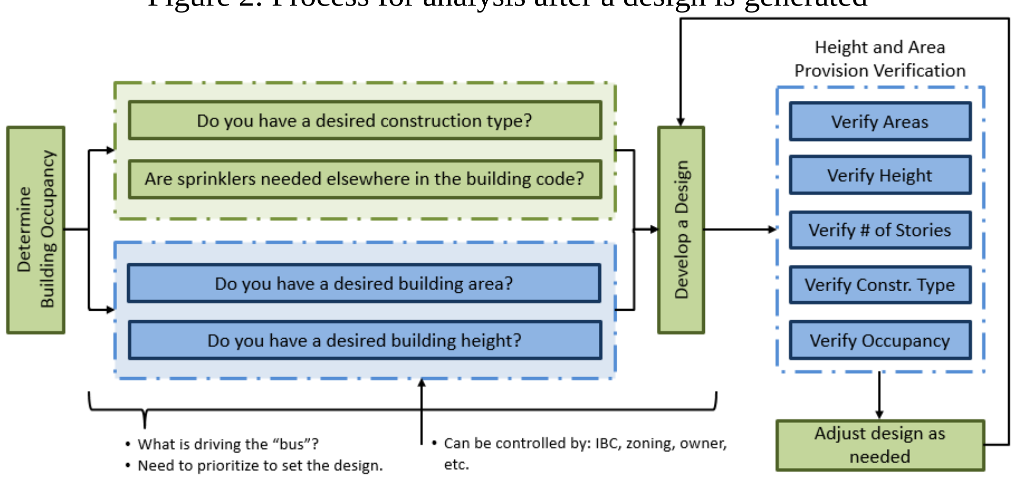

Figure 3: Process if considered during Design Iterations.

Height, area and stories shall not exceed limits within the IBC based on construction type and occupancies. For the IRC these limitations are built into the basis of the code as part of the scope of the IRC. IBC sections that control design are§504.3 max. height, §504.4 max. number of stories, and§506.2 area per story (ICC 2015b). Building height, number of stories and building area provisions are always applied independently and all must be satisfied. In a building containing mixed occupancies fall under IBC section 508 that says that no individual occupancy shall exceed the height and number of story limits specified for the applicable occupancies.

Table 504.3 (Figure 4) indicates the maximum allowable heights (ICC 2015b). Here only a partial table is shown, but it indicates the limitations for height of all R Group uses based on sprinkler type and construction types. Generally speaking, the better the quality of construction type and the less materials that are flammable within a construction type, then the taller a building can be.

OCCUPANCY CLASSIFICATION	SEE FOOTNOTES	TYPE OF CONSTRUCTION								
		TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
		A	B	A	B	A	B	HT	A	B
A, B, E, F, M, S, U	NS[b]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
H-1, H-2, H-3, H-5	NS[c, d]	UL	160	65	55	65	55	65	50	40
	S									
H-4	NS[c, d]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
I-1 Condition 1, I-3	NS[d, e]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
I-1 Condition 2, I-2	NS[d, f, e]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85						
I-4	NS[d, g]	UL	160	65	55	65	55	65	50	40
	S	UL	180	85	75	85	75	85	70	60
R	NS[d, h]	UL	160	65	55	65	55	65	50	40
	S13R	60	60	60	60	60	60	60	60	60
	S	UL	180	85	75	85	75	85	70	60

Figure 4: Representative and Reproduced Sample of Table 504.3

Table 504.4 (Figure 5) indicates the max. allowable No. of stories (ICC 2015b). The maximum allowable height in stories can vary significantly based on the occupancy group. In general, the greater the potential fire- and life-safety hazard, the fewer the number of permitted stories there can be. As Figure 5 highlights, unless you have type 1 Construction (steel and or concrete) where stories can be as tall as 11 stories to unlimited, then your R classified building must be 4 stories or less.

OCCUPANCY CLASSIFICATION	SEE FOOTNOTES	TYPE OF CONSTRUCTION								
		TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
		A	B	A	B	A	B	HT	A	B
R-1	NS[d, h]	UL	11	4	4	4	4	4	3	2
	S13R	4	4						4	3
	S	UL	12	5	5	5	5	5	4	3
R-2	NS[d, h]	UL	11	4	4	4	4	4	3	2
	S13R	4	4	4					4	3
	S	UL	12	5	5	5	5	5	4	3
R-3	NS[d, h]	UL	11	4	4	4	4	4	3	3
	S13R	4	4						4	4
	S	UL	12	5	5	5	5	5	4	4
R-4	NS[d, h]	UL	11	4	4	4	4	4	3	2
	S13R	4	4						4	3
	S	UL	12	5	5	5	5	5	4	3

Figure 5: Representative and Reproduced Sample of Table 504.4

In regards to allowable area, both Use and occupancy of the space along with Construction type play a role. The intent for considering use and occupancy of the space focuses on the amount of combustibles attributable to the use that determines the potential fire severity including the number of people that need to be evacuated. For construction types, they correlate to the amount of combustibles in the construction of the building, which contributes to the potential fire severity. Other impacts on area include if there are sprinklers and the amount of frontage on the property. Essentially area is formulated around how robust the construction type is against fire determines how long the structure will survive a fire.

When we have more than one occupancy in a single building that contains residential, multiple areas are permitted when the allowable area of the most restrictive occupancy is used for non-separated occupancies or when the occupancies are regulated as a separated occupancies the IBC allows somewhat larger floor areas. Table 506.2 (Figure 6) indicates the allowable area factor (not adjust for frontage) (ICC 2015b).

OCCUPANCY CLASSIFICATION	SEE FOOTNOTES	TYPE OF CONSTRUCTION								
		TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
		A	B	A	B	A	B	HT	A	B
R-1	NS[d, h]	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
	S13R									
	S1	UL	UL	96,000	64,000	96,000	64,000	82,000	48,000	28,000
	SM	UL	UL	72,000	48,000	72,000	48,000	61,500	36,000	21,000
R-2	NS[d, h]	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
	S13R									
	S1	UL	UL	96,000	64,000	96,000	64,000	82,000	48,000	28,000
	SM	UL	UL	72,000	48,000	72,000	48,000	61,500	36,000	21,000
R-3	NS[d, h]	UL	UL	UL	UL	UL	UL	UL	UL	UL
	S13R									
	S1									
	SM									
R-4	NS[d, h]	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
	S13R									
	S1	UL	UL	96,000	64,000	96,000	64,000	82,000	48,000	28,000
	SM	UL	UL	72,000	48,000	72,000	48,000	61,500	36,000	21,000

Figure 6: Representative and Reproduced Sample of Table 506.2

As can be seen in Figure 6, for type one construction, no matter the classification of the R Group, unlimited area is permitted. For larger scaled projects this is often the default construction type that must be used. An additional item to note is that for R-3 occupancies, all 5 construction types permit unlimited area. This classification of R can have advantages here from a usable footprint for the owner.

Summary Discussion

The discussion of residential buildings in this paper has included buildings that fall within the IRC and the IBC. The main distinguishing factor between the two codes is the number of stories but also the occupant type and scale. While the IRC is predominately prescriptive in nature, once outside its scope the IBC takes a more formal engineering approach to residential, causing the provisions to be both prescriptive and performance.

While the paper has only scratched the surface on the residential requirements for R-Group Buildings, the provisions discuss have major impacts on the applicability of uses, materials used and permission size of the project. It is clear though that owners and builders/designers need to clearly discuss their goals and performance objectives to properly select systems, configurations, uses and boundaries so that the design can be achieved. Whether they are engineered or prescriptive, the design intent must be achieved and code provisions satisfied in order to obtain occupancy permits.

The work presented indicates that there are multi-criteria metrics that form interconnected relationships that drive design decisions. Inner connected parameters include: construction types, occupancy classification (R-1 to R-4), single or multi-use, sprinkler type, height, area, and finally number of stories. Change any one of these and the others can and mostly likely will adjust the other boundaries.

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Residential Building Lifespan and Community Resilience

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Abstract

Developing meaningful estimates of the life cycle impacts of a building relies on setting an appropriate estimate of the building's lifespan. Nevertheless, most conducted LCA studies are based on an arbitrary building lifetime. This research, focuses on modeling the lifetime of housing stock divided by decade of construction (a 'cohort') in order to generate a probabilistic assessment of residential building turnover. Data from the American Housing Survey (AHS) National Summary Reports and the New Residential Construction Housing Starts (NRC) was compiled and analyzed. Relevant data was extracted and then analyzed both in its raw format and as a set of normalized curves.

The results show that each cohort of housing from the 20th century behaves in a similar way when normalized, although there is not yet enough data to definitively pinpoint the average lifespan of housing stock since the available data does not suggest a "peak" in the number of demolitions reached. The existing data suggests that housing longevity exceeds the previously accepted average of 61 years and can vary from cohort to cohort, potentially due to economic conditions at the time of construction and demolition.

Assuming a range of possible lifespans for individual buildings, a Monte Carlo Simulation was performed and further revealed that the turnover time of a community housing stock is determined by the characteristics of the typical housing units within the community and can be significantly longer than average housing lifespan estimates.

Keywords

Housing stock lifetime; Residential buildings; Demolition; Housing turnover; Life Cycle Assessment

1 Introduction

Buildings are responsible for nearly half of the CO_2 emissions in the United States (Architecture 2030, 2017). In order to confront the reality of climate change within the building industry, the life-cycle assessment (LCA) approach has been used to quantify the carbon footprint of existing and projected structures from cradle to grave. The carbon footprint of a typical existing building consists of embodied impact associated with manufacture and construction, and operational impact that accumulates throughout that building's lifetime as well as end of life waste treatment and recycling. While the relationship between the two varies from building to building, operational impacts of existing housing stock tends to outweigh the embodied impact, constituting as much as 80-90% of the total carbon footprint (Basbagill et al., 2013). Therefore, an accurate LCA relies on setting the frame of assessment at the entire lifespan of a particular building - although most conducted LCA studies are based on an arbitrary building lifetime ranging between 50 to 100 years (Mequignon et al., 2013).

Often, housing lifetime is dependent on an array of uncertain factors such as age, economic context and desirability. In the US, residential construction longevity appears to be more directly related to social acceptability factors rather than durability at the time of construction, although both factors play a part (Winistorfer et al., 2007). Even though the task of modeling housing lifetime is difficult, a few extrapolative approaches were made by Michael Gleeson in the 1980s. Gleeson first proposed modeling housing "mortality" as a Gompertz curve, a model used by actuaries to predict human mortality (Gleeson, 1981). In later publications (Gleeson, 1985), the Weibull and the Pearl-Reedman curves were also suggested as possible statistical approaches to housing longevity. Unfortunately, at the time of publication of these models 30 years ago, data on US housing stock was lacking - the Census had only conducted the American Housing Survey for 10 years, which was not sufficient to validate any one projection over the other.

More recently, existing data on housing stock was compiled by Aktas and Bilec in an attempt to determine what the average housing lifespan in the U.S. currently is. Their approach yielded a deterministic average housing lifespan of 61 years based on microdata collected from 1997-2009 (Aktas & Bilec, 2012). The further application of a range of housing lifespans to a sample LCA calculation determined that lifespan drastically influences the outcome of the analysis.

The goal of this research is to investigate patterns of demolition among existing data by splitting up the housing stock into cohorts by decade of construction. This method creates an opportunity to observe any major deviations in demolition patterns from cohort to cohort, which may then be investigated further and attributed to economic or desirability factors. Gleeson's hypothetical curves were tested against existing data and the Aktas and Bilec microdata approach repeated with a sensitivity to decade of construction as a factor that affects housing lifespan.

Even though advances in sustainable construction will play a key role in new projects, existing housing stock will not be demolished overnight. A model of demolition based on housing age was applied to an existing community in a Monte Carlo Simulation to project the likelihood of housing turnover over time. Analyses like the one discussed in this paper can inform city planners on how to transition to sustainable community building – determining which houses should be retrofitted, and which ones will likely be demolished in the near future in favor of greener construction.

2 Methods

Methods used to compile and analyze data for modeling housing lifespan are described in this section. Two approaches are highlighted - one based in using national summaries and one relying on individual microdata as previously done by Aktas and Bilec. The procedure of statistically fitting the existing data to extrapolative curves described by Michael Gleeson in his previous work on housing longevity is documented. Finally, the first models of housing longevity and its possible influencing factors are presented.

2.1 Data sources

In the scope of the summary approach, data published by the Census in the American Housing Survey (AHS) National Summaries for each release between 1970-2013 was compiled for preliminary analysis of housing demolition trends. In order to compare demolition data to housing starts, the New Residential Construction (NRC) Housing Starts from 1960-2013 was consulted. In the microdata approach, relevant housing unit age and demolition microdata from the 1997-2009 AHS National releases was collected and analyzed. (US CensusBureau, 2017)

2.2 National Summary Analysis

AHS data from each release of the national summary report between 1970-2013 was compiled. In each report, the projected number of housing under each category in the "Year Structure Built" subsection of Table A-1 (Characteristics of Housing Inventory) was then extracted. In some cases, the data was compiled into a single decade of construction - for example, housing built in 1960-1965 and 1965-1969 was combined into one "1960 cohort". Data from the NRC table was similarly compiled. The projected presence of each housing cohort in the US was then plotted against each used AHS and NRC survey year and preliminary lines of best fit were developed using MS Excel (figure 1).

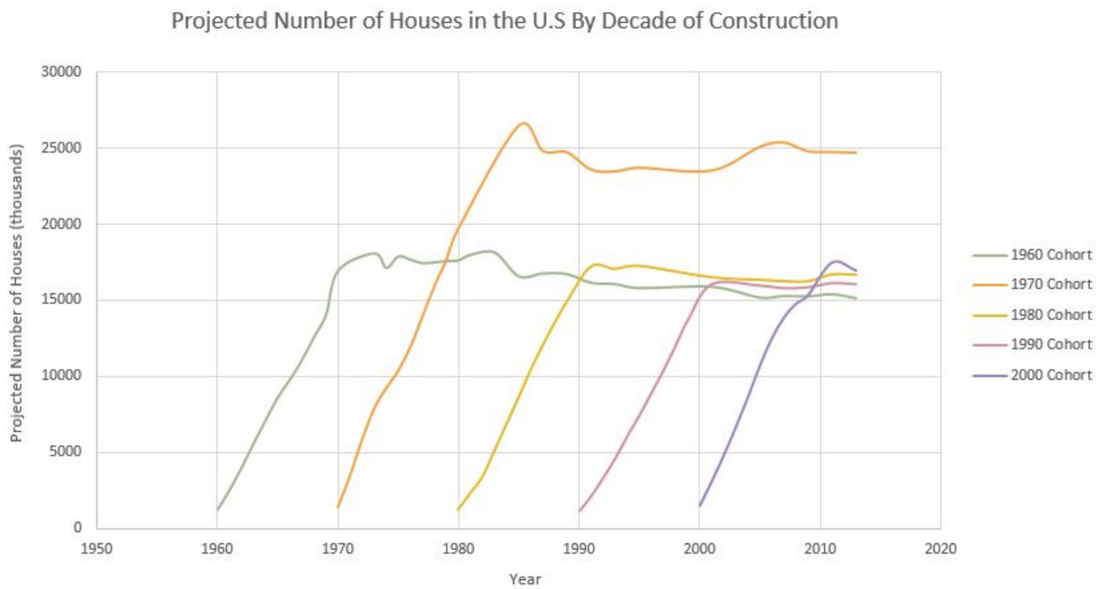

Figure 1. Projected Number of Houses in the US (by decade constructed or 'cohort')

All the available data from 1970-2013 AHS surveys that indicates the projected number of housing units by cohort was then plotted against the number of years that have passed between the starting date of the cohort's construction and the year of the survey (figure 2). The cohort was assumed to start in the first year in the decade - for example, if the 1920s cohort data was recorded in the 1985 AHS survey, it was assumed that 65 years have passed since the cohort's genesis in 1920.

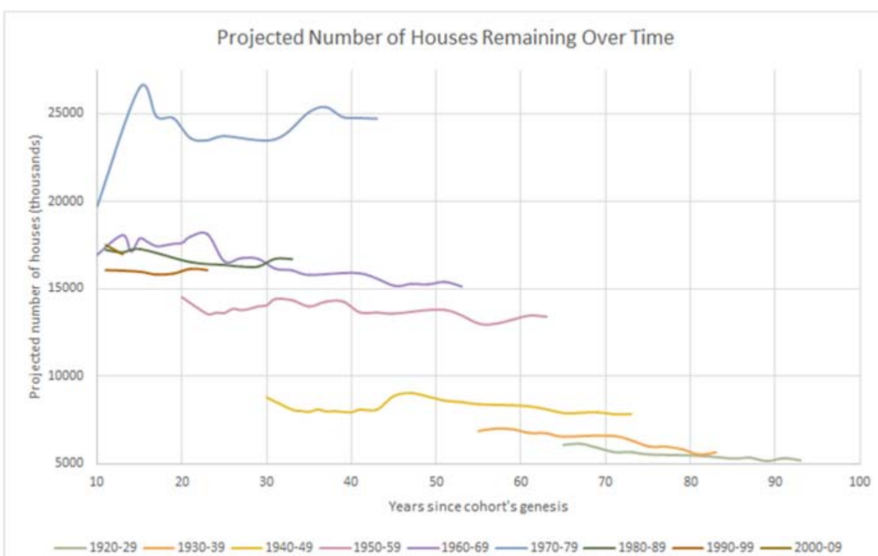

Figure 2. Projected Number of Houses in the US over time since construction

Additional analysis of data was completed through attempting to normalize each cohort's data by setting the first known projected quantity of housing units built in a particular decade to 100% and comparing the following values against this initial factor as follows:

$$R = \frac{S}{I} \times 100\%$$

Where R is the percent of housing stock remaining, S is the projected number of each cohort's housing stock obtained from an individual AHS survey and I is the initial projected number of a cohort's housing stock set at the first recorded value after the housing cohort's construction period is complete (10 or 11 years after a cohort's genesis). R was then plotted against the number of years that had passed since the cohort's genesis in the beginning of its corresponding decade (figure 3). For example, the 1960s cohort's genesis year was assumed to be 1960 - thus, the data pertaining to the 1960s cohort recorded in the 1974 AHS was assigned to represent the cohort's presence 14 years since genesis. This could only be done for housing built in the 1960s and onward due to lack of data on previous construction.

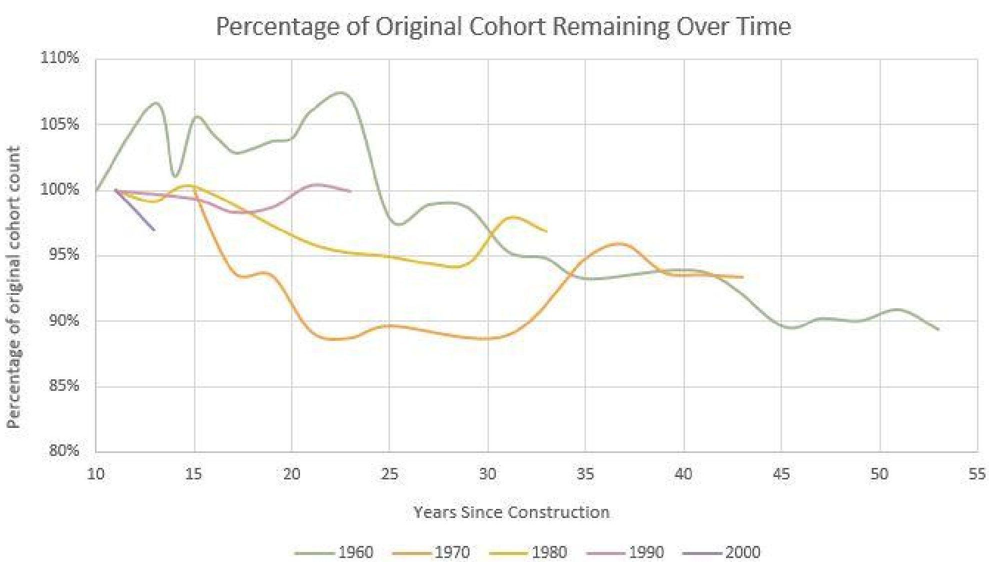

Figure 3. Percent of original cohort remaining over time (AHS Summary data)

2.3 Fitting curves to existing summary data

The data for the two oldest available cohorts (1960-69, and 1970-79) was compiled and exported into csv format and then analyzed using the grofit package in RStudio (figure 4). The previously suggested Gompertz and Weibull curves were tested against existing data. Thirty years after the publication of Gleeson's Gompertz projection, the data disproves it. Only the Weibull curve could be fitted to the oldest available cohort constructed in the 1960s, which is beginning to exhibit exponentially faster rates of demolition in the most recent years (50 years post-construction). For newer cohorts, the overall demolition rate is still fairly consistent, which indicates continued maintenance of individual houses and does not show a bias towards one projection. Ultimately, statistical approaches to the data set akin to Gleeson's are still extrapolative even with 30 more years of housing stock data.

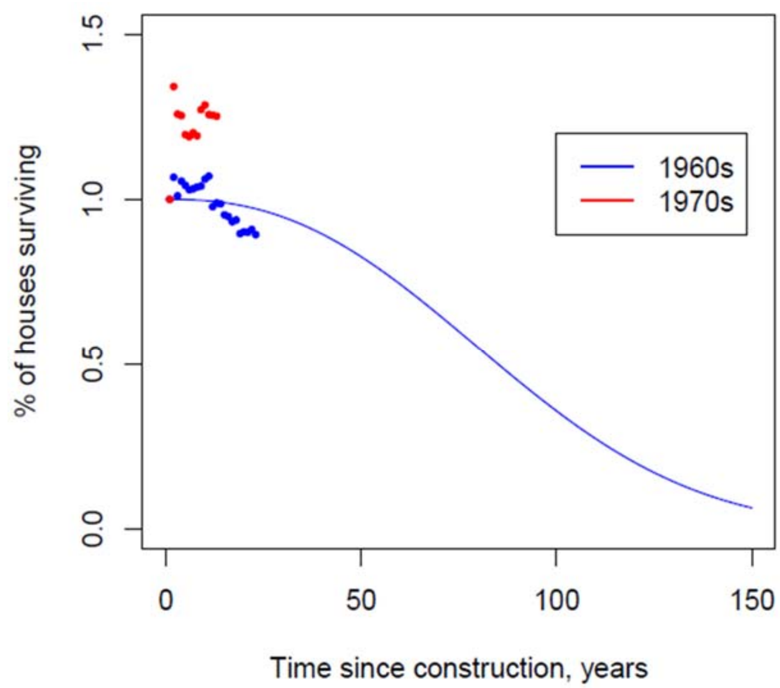

Figure 4. Weibull curve projection based on 1960s cohort summary data

2.4 AHS Microdata Approach

Another approach to investigate existing demolition patterns in the U.S. housing stock relied on the compilation of available microdata - approximately 60,000 individual responses to surveys in a given year. AHS microdata from 1997 to 2009 was compiled (US CensusBureau, 2017). Only the data columns under code BUILT (year the interviewed house was built) and NOINT (no interview) were extracted. All the construction years were combined into construction decades - for example, if a housing unit was denoted as built in 1964, that value was replaced with 1960 to denote its designation as a member of the 1960s cohort. The response NOINT = 30 denotes that the house interviewed could not be interviewed in this particular year due to demolition, so the relationship between demolition and year of construction was investigated by comparing the two values in tandem. The number of demolished houses in each responding cohort in that year was then recorded and plotted against BUILT data as years since construction, which produced a plot of demolition of remaining houses over time (figure 5).

Figure 5. Number of houses demolished over time since construction (AHS microdata, 1997-2009)

The same data on demolition from separate surveys was then re-combined to track demolition of individual cohorts by year of construction. For example, the 9-year old houses that were described in the 1997 survey belonged to the same cohort as 11-year old houses in the 1999 survey and so on until 2009, at which point those houses collectively reached the age of 21 years old. In this way, individual cohorts of housing were tracked through their lifetime to observe patterns of demolition strictly tied to age (figure 6).

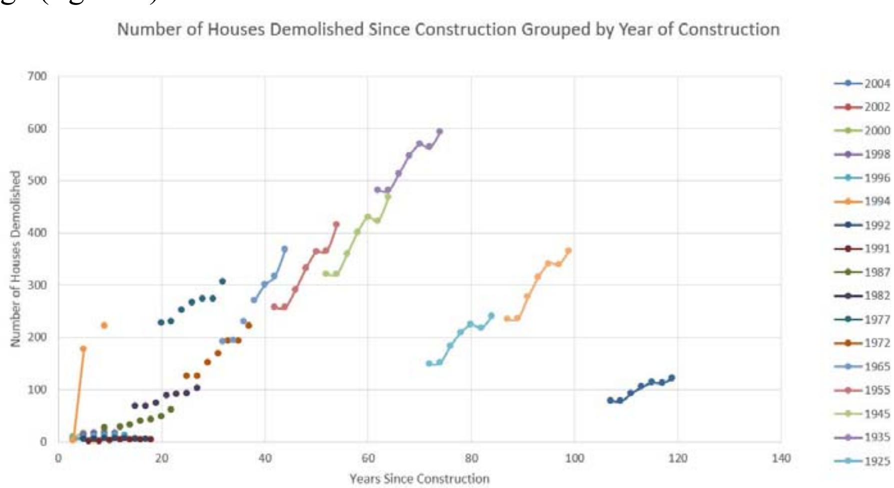

Figure 6. Grouping houses by cohort to track behavior over time

To gain further insight, this plot was then normalized by setting the total number of houses belonging to a particular construction year in a survey to 100% and calculating the constituent percentage reported as demolished (figure 7).

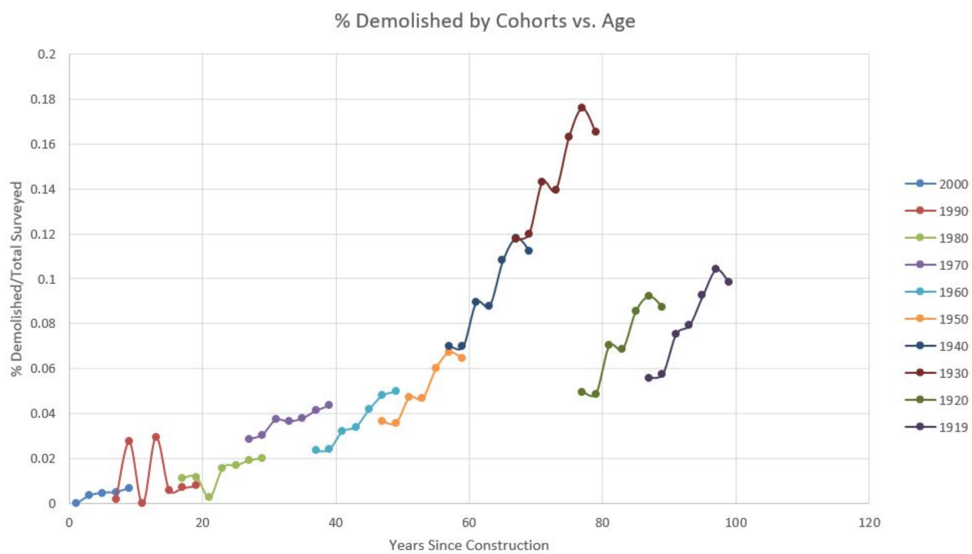

Figure 7. Normalization of cohort demolition behavior over time (comparing to total number of houses surveyed within that cohort)

2.5 Economic correlation

Housing demolition is a complex issue that does not depend on age alone. Another factor that may influence housing mortality is the state of the economy at the time of construction and demolition. A plot comparing housing starts from the NRC and demolitions reported in AHS microdata was produced to visualize the impact of economics on the housing market in the recent years.

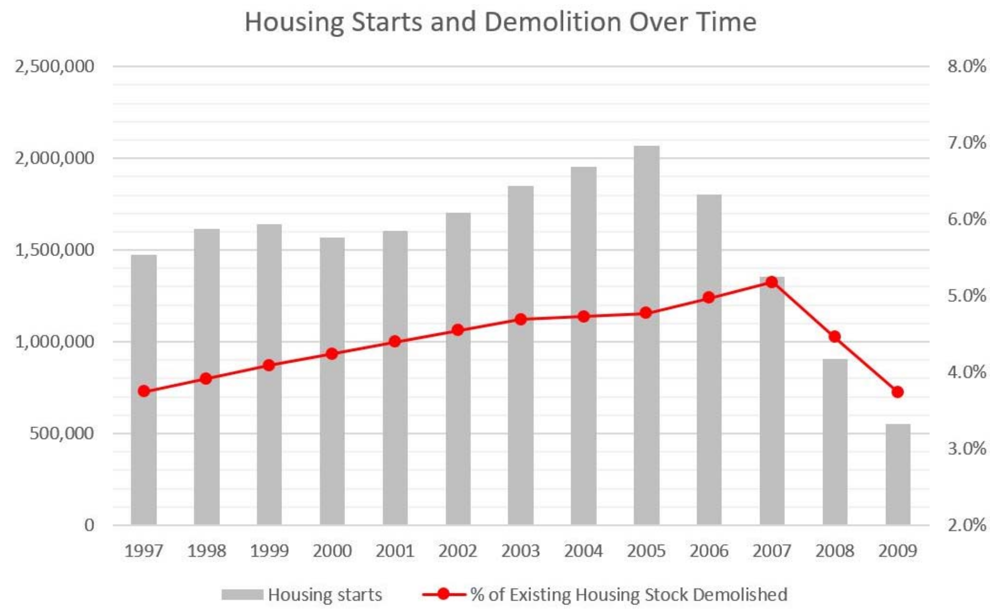

Figure 8. Housing starts and demolition in the recent years, potentially tied to economic factors.

3 Discussion

3.1 Methods

The summary method was not very informative due to major data inconsistencies in the AHS due to its methodology. The 1970s cohort is the best example of this issue - even though the 1980 AHS recorded a projection of 19,733 thousand housing units built in the 1970s remaining, the 1985 AHS survey reported a sharp increase to 26,477 thousand housing units remaining. This accounts for the spike in the plot where data suggests that even though the initial number of 1970s housing units remaining in 1980 was taken to be 100%, five years later, 134% of that initial value was "remaining" in the United States. This inconsistency can be explained through the way the AHS is conducted - in the national summary reports, a large data set encompassing the entire nation relies on projections based off of 50,000 or so individual interviews, and not raw data from each individual household.

The microdata approach suffers due to limited data availability. In 2011, the AHS stopped simultaneously recording the NOINT=30 demolition response alongside with the age of the responding housing unit. In order for the same analysis to continue, this relevant data must be collected or other mechanisms developed to estimate this data.

3.2 Projections

Using statistical modeling software (R Core Team, 2017) to develop statistical models based on collected data affirmed the conclusion that there is not enough data to develop a true predictive statistical model of housing lifespan. Only the 1960s cohort had actually displayed a viable pattern that could be recognized as the beginning of a Weibull curve suggested by Gleeson in the 1980s. The ones following could not be processed by the script to produce a Weibull extrapolation, instead only suggesting a linear pattern. Even 40 years after construction, the 1970s cohort has not yet exhibited enough of a difference between adjacent data points of houses remaining to suggest a curve shape. However, the Gompertz curve has been disproved by the data from the past 40 years as a method of modeling housing mortality. Future projections of housing mortality will benefit from continued collection of data on a nationwide scale and comparison with the Weibull model.

3.3 Parameters

As the analysis shows, the decade of a construction of a house when it comes to predicting its demolition is a relevant factor that can affect the rate of demolition. However, the lifespan of housing stock is also linked to factors outside of building age, likely economic in origin. Recently, both housing starts and housing demolition decreased drastically following the 2008 market crash. It is likely that a similar economic impact was experienced by the 1930s cohort which is now causing the cohort's faster demolition rates. Another factor that may come into play with later analysis is build quality. Particular decades are likely associated with particular build quality throughout the past century – which may impact the desirability of a house over time and the likelihood of its upkeeping.

3.4 Applications in Community Scale Assessment

We extend the concept of lifespan range to investigate the turnover time (T_l^{BC}) of a community building cluster consisting of different archetypes. We define the variable T_l^{BC} as the time takes for 95% of buildings in the cluster to reach their lifespan, and estimate the statistics of T_l^{BC} using Monte Carlo Simulation (MCS).

To illustrate the concept, we assume a hypothetical building cluster (BC) consisting of two archetypes, B1 and B2. The lifespan statistics of B1 and B2, including mean, coefficient of variation (c.o.v.), and the scale parameter (k) and location (λ) parameter of the Weibull distributions that models the lifespan of individual buildings T_l, are tabulated in Table 1. A MCS using these statistics revealed that the mean turnover time of this building cluster T_l^{BC} is approximately 180 and is relatively invariant when this cluster size (or the total number of buildings in the cluster) varies, while the c.o.v. of T_l^{BC} decreases monotonically as cluster size increases, as shown in Figure 9.

Table 1. Statistics of the hypothetical building cluster

Type	Number	Lifespan statistics of individual buildings, T_l (Weibull distribution)			
		λ	k	mean	C.O.V.
B1	2n	112.84	2	100	0.52
B2	n	56.42	2	50	0.52

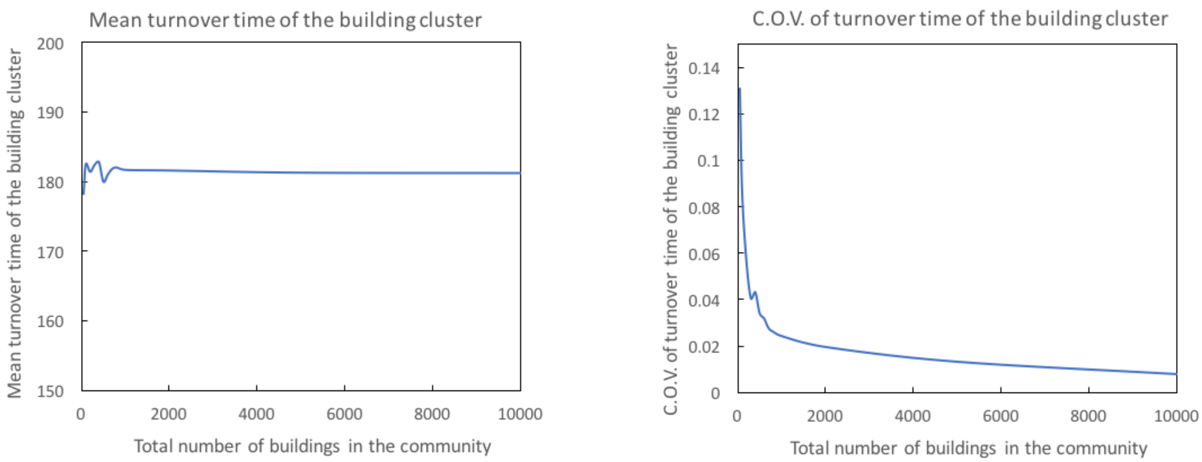

Figure 9. Mean and C.O.V. of turnover time of the building cluster

4 Conclusion

Based on currently available data, average residential building lifetime was calculated to be 56 years with a standard deviation of 25 years based on American Housing Surveys 1997-2009. However, this value cannot be used as a deterministic representation of housing lifespan in LCA due to the limited nature of the existing data set. While the mean of the data set is 56, the mode is at a significantly higher 64 years. The combined graph of demolition over time by cohorts (figure 7) suggests an increasing rate of demolition that has not yet reached a definitive peak. This suggests that data collected in the coming years will likely push the average upwards, perhaps to follow the Weibull curve projection to be as high as 75 years. This is consistent with Atkas and Bilec's projection of increasing housing lifespan - but the main reason for this is due to the accumulation of data over time, and not due to factors like increasing build quality or desirability. In Aktas and Bilec's analysis that yielded an average lifespan of 61 years, there is simply more data available on the more recent housing cohorts than there is on older ones, which means that the current average leans low - closer to the well-documented maintenance stage of housing demolition.

Microdata from the AHS supports a higher lifespan than the previous metric of 61 years proposed by Atkas/Bilec. When analyzed holistically, existing demolition data is highly influenced by the behavior of the 1930s cohort in particular, which is currently being demolished at the fastest rate. The behavior of the 1930s cohort may not be typical of housing units – likely due to economic conditions in the U.S. at that time that may have influenced the quality of construction during the great depression. Other cohorts such as the 1920s or the 1970s appear to be demolished at different rates, which suggests that using a deterministic approach to housing age may not be appropriate to calculating building LCA. Each cohort behaves differently, so a probabilistic assessment of a housing unit's lifespan that includes the year of construction may be more appropriate than choosing a single average. In modeling housing stock longevity, housing stock age is not enough to develop a deterministic model of its eventual demolition, so a probabilistic approach following a curve can be applied to individual cohorts – although the influence of economic factors as a parameter in the curve is still unclear.

Housing lifespan is best treated as a range of probable outcomes, rather than a single value. Parameters such as information on the build quality and current economic climate can increase the accuracy of this range as further models are developed. As it stands, the existing housing stock exhibits demolition behavior that can result in lifespans from 80 to 120 years, depending on whether the projected behavior follows the shape of a left-leaning, symmetrical, or right-leaning bell curve. In approaching community turnover or LCA for individual buildings, it would be most prudent to consider the upper and lower limit of possible lifetimes as well as the average, in order to have the most comprehensive look at housing lifetime and its impacts.

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PNNL-SA-129292

At the Core: Fundamental Building Science Education Matters More Than Building Type

Metzger CE[1], Rashkin S[2], Wagner A[1]

Abstract

As building enclosures become more advanced, the need for building professionals who know how to fully integrate building science best practices has increased dramatically. This is because advanced enclosures have less drying potential, greater challenges ensuring comfort systems have adequate mixing and humidity control, and less infiltration to dilute dangerous contaminants. However, both residential and commercial building professionals struggle to ensure high-performance because virtually all workforce classifications involved in designing, engineering, constructing, commissioning, assessing, operating, and transacting buildings do not have adequate and consistent levels of competency to apply relevant building science skills.

To help address this need, the U.S. Department of Energy's (DOE's) Residential Building Integration (RBI) program initiated the *Guidelines for Building Science Education (GBSEs)*. These guidelines set clear levels of competency for fundamental building science knowledge and skills that are essential across a full spectrum of workforce classifications involved in the building industry. This effort is intended to create a common agenda nationwide for training organizations, industry associations, trade associations, colleges[3], and universities to align their core curriculum and help ensure the current and next generation of building professionals are prepared to effectively integrate building science. These guidelines are a living document that will continually benefit from review, comments, and submissions of the many collaborators working with this initiative.

At the same time, DOE's Commercial Building Integration (CBI) program has been spearheading the *Better Buildings Workforce Guidelines (BBWGs)* which provide voluntary national guidelines from which select stakeholders can develop high-quality and nationally recognized training and certification programs. Currently, the BBWG framework targets improved quality and scalability issues for five energy efficiency-related jobs: Building Energy Auditor, Building Commissioning Professional, Building Operations Professional, Building Operations Journey-Worker and Energy Manager.

The residential and commercial building programs are both interested in facilitating better buildings through an improved workforce. The two program initiatives complement each other in many ways. The GBSEs pave the way for establishing a national platform for consistent building science competency across a comprehensive set of workforce classifications involved in the building industry while the BBWGs provide much more rigorous programs for credentialing and certification for a much smaller subset of commercial building professionals. GBSE will be positioned to refer their stakeholders to the BBWG, especially as it expands their scope of workforce classifications. This paper summarizes the steps DOE programs have taken to work together and the outcome of this symbiotic relationship.

1.0 Introduction

The U.S. Department of Energy's (DOE's) Residential Building Integration (RBI) and Commercial Building Integration (CBI) programs have provided funding to the Pacific Northwest National Laboratory (PNNL) to help establish a cohesive program that focuses on creating better buildings through an improved workforce. The two programs have some similarities and some differences which determined the most productive way to integrate them together. More detail is provided in the sections below.

[1] Pacific Northwest National Laboratory
[2] U.S. Department of Energy
[3] Also, includes workforce development programs at two-year colleges

PNNL-SA-129292

1.1 Similarities and Differences between the Original Residential and Commercial Efforts

The two original workforce guideline programs from RBI and CBI have many similarities. Both of them

- focused on improving building performance through an improved workforce,
- used industry involvement and input to develop guidelines for specific job classifications, and
- promote their guidelines with key organizations involved in training, educating, credentialing, and certifying building industry professionals.

The differences between these programs are three-fold, as shown in Figure 1:

1. **Framework -** BBWGs focus on five specific job classifications, while the Guidelines for Building Science Education (GBSEs) focus on a much broader range of job classifications (see Section 4.1).
2. **End Goal -**The BBWG program seeks to provide a framework for knowledge, skills, and abilities that support specific tasks identified by the BBWGs, whereas the goal of GBSE program seeks to provide more broad and comprehensive building science knowledge and skills.
3. **Partner Strategy -** , The BBWG program is a much more exclusive partnership that requires a rigorous accreditation process to achieve DOE recognition, while the GBSE program aims to collaborate iteratively with as many organizations as possible to incrementally align with its national guidelines.

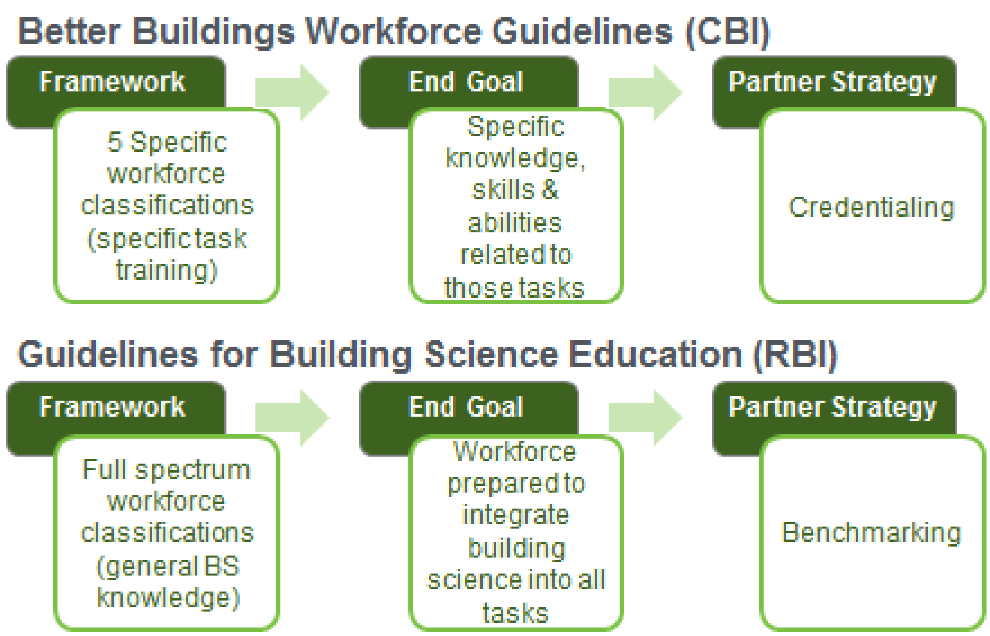

Figure 1. Comparison of Residential and Commercial Guideline Program Elements

2.0 Integration of the Better Buildings Workforce Guidelines

The ongoing collaboration between the RBI and CBI programs has the following three main goals:

1. Ensure that the GBSEs and the BBWGs are fully aligned.
2. Ensure that the residential and commercial buildings industries are equally well represented in the final products.

3. Provide a distinct but complementary path for users/stakeholders of the GBSE and BBWG programs to improve the energy efficiency of buildings.

2.1 Addressing Goal 1 and 2

Prior to this coordinated effort, the RBI program hosted numerous meetings and review sessions with dozens of stakeholders to help capture valuable input from the residential building industry related to the GBSEs. Once a coordinated path forward was established, the Pacific Northwest National Laboratory (PNNL) conducted an industry review to determine whether any commercial buildings job classifications or competency topics were missing from the original guidelines. Any missing job classifications and competency recommendations were vetted by the management team (including the National Institute of Building Sciences [NIBS]) and presented to the Commercial Workforce Credentialing Council[4] for review, comment, and approval.

2.2 Addressing Goal 3

Ultimately, the BBWGs and GBSEs are complementary and integral to each other. To provide useful resources to all relevant workforce classifications, the GBSE program benchmarks proficiency levels relevant to building science knowledge and skills customized to a comprehensive range of workforce classifications related to the building industry. The BBWGs build on the GBSEs and provide accreditation for programs that meet or exceed their requirements for ensuring high-efficiency commercial buildings. At this time, the BBWG program focuses on accreditation for five job classifications:

- Building Operations Professional,
- Building Operations Journey-Worker,
- Building Commissioning Professional,
- Commercial Buildings Energy Auditor, and
- Energy Manager

BBWG has a goal is to achieve more accredited options in the future as needs arise.

The BBWG jobs generally represent requirements for master level professionals recognized through the certifications of individuals. To complement these high-level certifications, the BBWG and GBSE programs are also working together to develop less rigorous options for recognizing education programs where appropriate. The goal is to provide a comprehensive range of workforce classifications with the opportunity to expand their pool of qualified workers with critical building science skills. Ultimately, this will help provide the ability to improve the performance of buildings nationwide.

3.0 Result of Program Integration

DOE's GBSE initiative recognized early in its outreach to the building industry that a resource was badly needed to help collaborators apply the guidelines in their training and education. This led to the development of the Building Science Education Solution Center (BSESC) as an online tool that serves as a repository for content fully aligned with GBSE. The expectation is for the BSESC to be continuously improved with collaborators identifying, reviewing, and sharing content. It will also leverage content from the DOE Building America Solution Center and other sources. Ultimately, the goal is to provide all

[4] The Commercial Workforce Credentialing Council is an organization that was established by NIBS to lead the development of the BBWG. More information is located here: https://www.nibs.org/?page=cwcc .

building industry stakeholders with the most up-to-date resource that reflects the latest research and scientific consensus. As a result of the program integration, job classifications, collaboration opportunities, and the original BSESC website have been updated. The updates are elaborated on below.

3.1 Updated Job Classifications

The following job classifications are the final result of the collaboration effort between the RBI and CBI programs. The 34 listed jobs would benefit from some fundamental building science knowledge. Jobs that are covered by the more rigorous BBWGs are noted in parenthesis.

Builder/Remodelers
building owner
builder/general contractor (owner)
builder/general contractor (foreman)
insulation contractor
HVAC/mechanical contractor
plumber
home performance contractor

Program and Project Managers
utility program manager
"Green" building certification professional
building operations professional (see BBWG),
facility manager

Transaction Professionals
real estate agent
appraiser
building inspector
insurer
underwriter

Design and Construction Professionals
architectural engineer
architect
mechanical engineer
electrical engineer
lighting designer
civil/structural engineer
material science engineer
interior designer
building landscape architect
construction manager

Building Science Professionals
building forensic professional
commissioning professional (see BBWG)

Energy and Code Professionals
commercial building energy auditor (see BBWG)
residential energy auditor
residential performance assessor
commercial building energy manager (see BBWG)
commercial building energy manager (see BBWG)
building code official

3.2 Updated Building Science Education Solution Center

The BSESC (http://bsesc.energy.gov) was updated to include content from the BBWG program. The background content, stakeholders, and training content were updated to include any relevant information about the BBWGs or commercial buildings in general. Example pages from this website are shown in Figure 2 through Figure 4 below.

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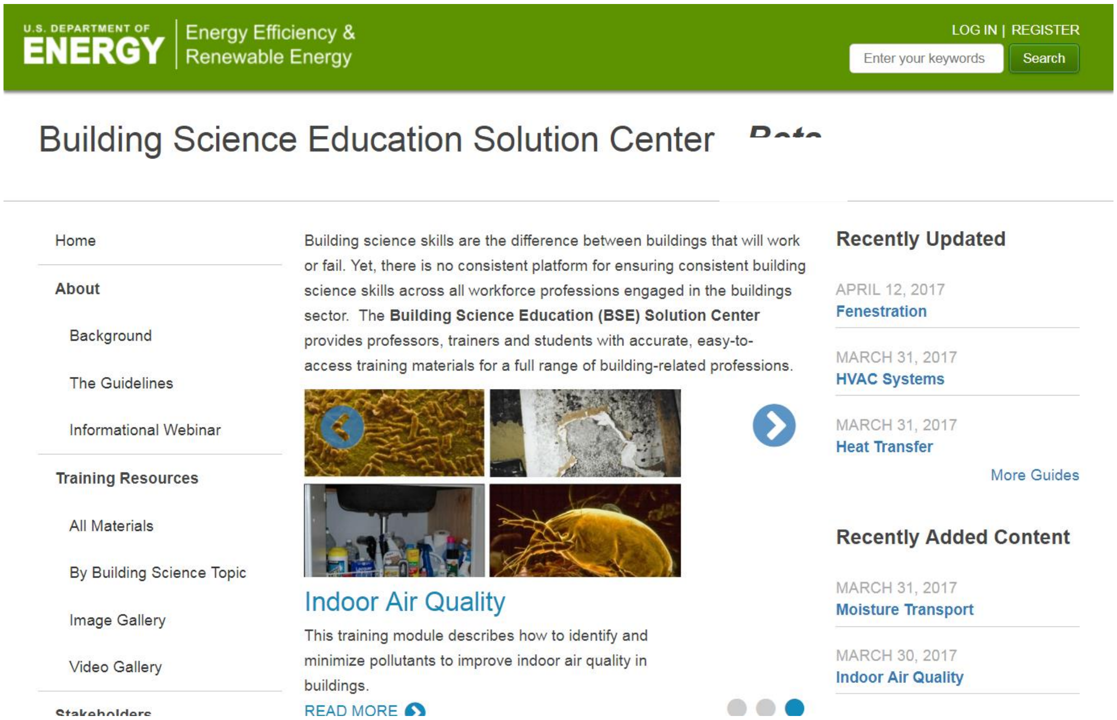

Figure 2. Homepage

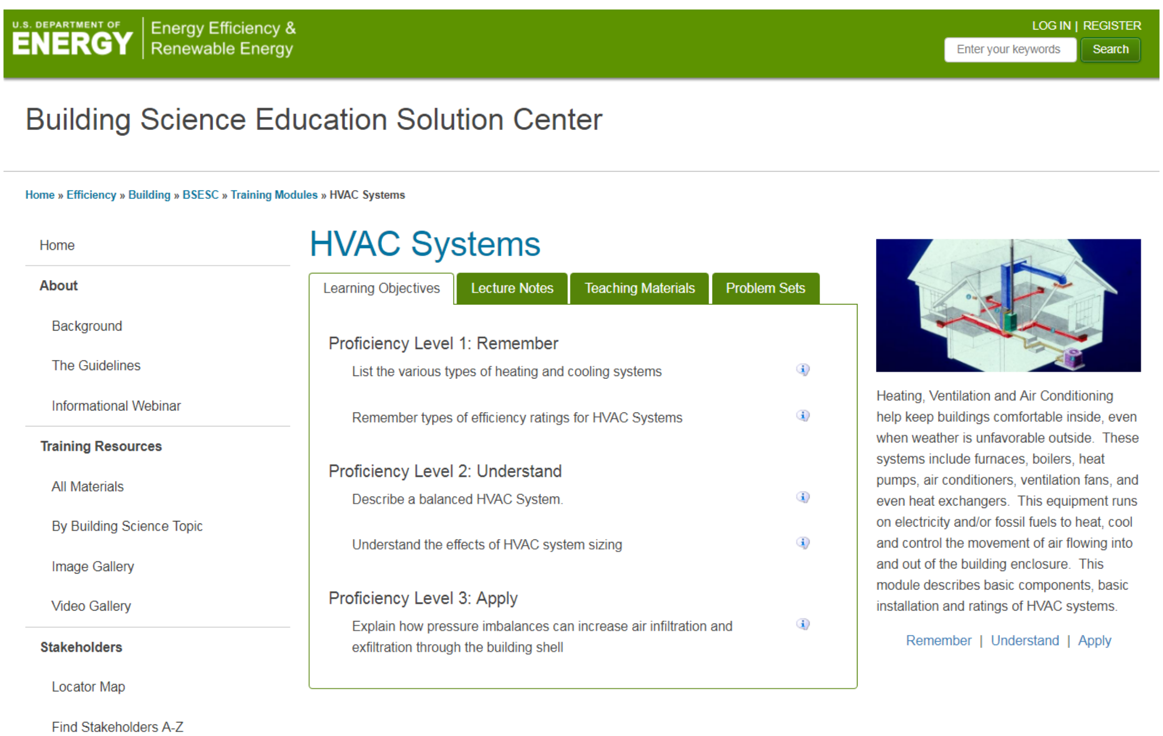

Figure 3. Example Core Competency Topic – Learning Objectives Tab

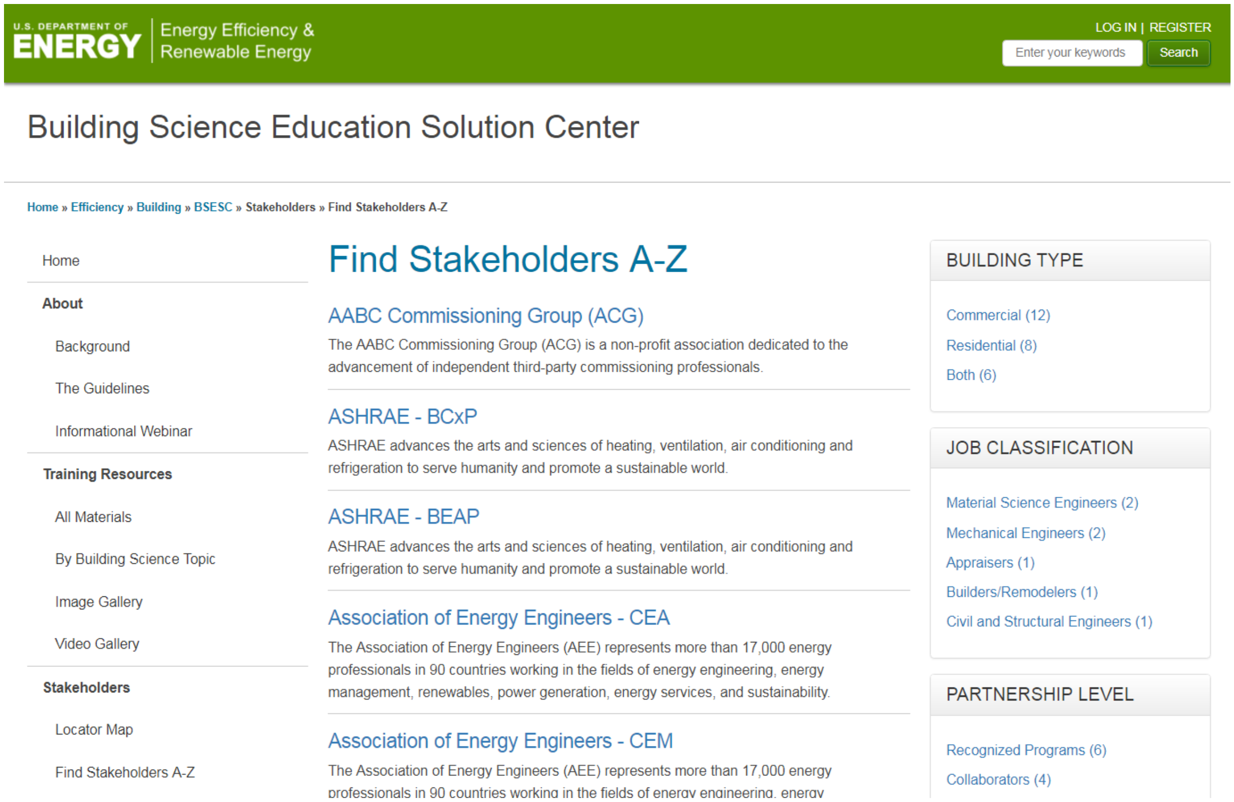

Figure 4. Stakeholder Landing Page – Including Both RBI and CBI Stakeholders

3.3 Updated Collaboration Opportunities

DOE now offers three types of collaboration opportunities in building science education/workforce development (listed below). The first two types are related to the GBSE (for more information contact Cheryn.Metzger@pnnl.gov). The third type is available through the BBWG process (for more information visit the Better Buildings website).

- *Collaborator* – Individual or organization that provides (or peer reviews) content that is used on the BSESC website.
- *Stakeholder* – Organization that helps to develop or implements a guideline for a relevant job classification.
- *Recognized by the BBWG* – A certification program that is aligned with the BBWG program and has received qualified accreditation by the American National Standards Institute, International Accreditation Service, or other bodies that can accredit to ISO/IEC 17024:2012, "Conformity assessment – General requirements for bodies operating certification of persons." A certification program that is aligned with the BBWG program and has received qualified accreditation by the American National Standards Institute, International Accreditation Service, for ANSI/ASTM 2659-15, *Standard Practice for Certificate Programs*, or by the International Renewable Energy Council (IREC) for ANSI/IREC 14732-14, *General Requirements for the Accreditation of Clean Energy Certificate Programs*.

4.0 Conclusions

The U.S. Department of Energy's (DOE's) Residential Building Integration (RBI) and Commercial Building Integration (CBI) programs have been motivated by the understanding that a diverse set of

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players work more effectively together than they do solely as individuals. The ***"Collective Impact"*** concept is the subject of a research paper by John Kania and Mark Kramer that was published in the winter 2011 edition of the *Stanford Social Innovation Review*. The authors' research revealed examples of "remarkable exception" for implementing large-scale social change and a common basis for their success.

By engaging a diverse set of educators in working toward a common goal, the collective influence on the market is exponentially more impactful than the incremental influence of individual organizations. Both the residential and commercial building programs at the DOE have engaged their stakeholders and each other in a way that provides efficient use of resources with a common goal toward achieving a more educated workforce ready to fully integrate critical building science knowledge and skills required for high-performance buildings. Results from this coordinated effort include a full suite of options for industry engagement and an updated BSESC.

5.0 Acknowledgements

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AN EXPLORATORY STUDY OF THREE PATHS TO GREEN HOMES:
Energy Star Homes, LEED for Homes, and the National Green Building Standard

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ABSTRACT

Residential green building rating systems are known for their ability to assist in the development of high-efficiency residential buildings, also known as green homes. Because these systems seemingly deliver similar products, there is much confusion among builders, consumers, and local governments about the similarities and differences of these programs. The Energy Star for Homes, LEED (Leadership in Energy and Environmental Design) for Homes, and National Green Building Standard (NGBS) are three nationally adopted residential green building rating systems that have a common goal, but utilize different processes for awarding certification. This study aims to compare the certification processes of these three systems. When comparing credit and documentation requirements, phases of the certification process and delivery process were considered. Credit requirements for the LEED and NGBS systems were evaluated in a side-by-side comparison to determine in which phase credits were earned. Process flow diagrams were used to map the certification process and identify points for documentation requirements. Eighteen builders and third-party raters that had previous experience with at least one of these three nationally adopted systems were interviewed to discuss their experience with the certification process. The findings of this study expand existing comparisons when considering the similarities and differences of the systems and gives insights to rating system selection to meet the needs of builders, consumers, and local municipalities.

INTRODUCTION

The original concept of sustainable development was defined in 1987 as “development that meets present needs without compromising the ability of future generations to meet their own needs” (Brundtland 1987). Green buildings are one facet of sustainable development, which is the practice of using healthier and more resource efficient models of construction, maintenance, operation, renovation, and demolition (EPA 2013a). Green buildings, also known as sustainable, eco-friendly, or high-performance buildings are defined as high performance buildings that promote resource efficiency, occupant health, and minimize environmental impacts using sustainable principles (Kibert 2008). Green building rating systems verify the efforts through the use of third-party raters who guide and certify the work put in place.

Three residential green building rating systems; Energy Star Homes, LEED for Homes, and the National Green Building Standard (NGBS) have been nationally adopted and accepted by builders in the construction industry (Reeder 2010). But this acceptance has not come without confusion. Studies have shown that builders, consumers, and local governments are confused about the similarities and differences of these systems (AIA 2010; Ruegemer and Smith 2012;

NAHB 2008; FitzGerald 2011). This study aims to compare and present the certification processes of these three systems.

BACKGROUND

Green building rating systems seek to lower environmental impacts of buildings through the use of sustainable techniques, strategies, materials, and performance testing. The International Energy Conservation Code (IECC) and the HERS (Home Energy Rating System) Index are two fundamental influences in residential building systems.

The IECC is a building code that specifically refers to energy efficient building practices for commercial and residential construction. It is updated every three years and can be adopted by state and local governments (ICC 2014a). Many residential green building rating systems use the IECC as a baseline and require practices that exceed the IECC by a given percentage.

HERS Index is the national industry standard for energy efficiency evaluation in residential construction, therefore is also a key component in green home rating systems. It calculates a home's potential to reduce energy demands through site testing (RESNET 2014). Performance testing ensures that the systems in place can perform to the level of efficiency designed (RESNET 2014). The rating ranges from 150 to 0, where a home that earns a HERS Index of 100 is in conformance with the 2006 IECC. The lower a HERS Index is the more energy efficient the home. HERS Index is used in each of the three rating systems examined in this paper: Energy Star for Homes, LEED for Homes, and NGBS. Table 1 below presents a comparison of all three systems.

Evaluations in the literature have compared these green residential building rating systems in regards to energy performance, cost of compliance, and minimum requirements. Couple of observations from these studies arose:

1. Energy Star program has a focus in energy and affordability but is limited in scope. The system does not include sustainable building practices that focus on passive systems, project site, or owner education (Reugemer and Smith 2012).
2. Several studies have examined the cost of compliance of residential systems and findings have consistently named LEED as the system with the highest cost of compliance. On the contrary, this program has also been praised for its rigidity and mandatory site testing requirements (FitzGerald 2011; NAHB 2008; AIA 2010).
3. The NGBS has been favored by some researchers for its prescriptive nature; where its credits are written using code language in an effort to appeal to a mainstream audience of builders (Reugemer and Smith 2012; FitzGerald 2011).
4. A common finding among comparisons is the significance of energy efficiency. Energy efficiency measures are consistently responsible for the highest percentage of the project costs (Reugemer and Smith 2012; FitzGerald 2011; NAHB 2008; AIA 2010).

Table 1: National Residential Green Building Rating Systems

	Energy Star Homes	LEED for Homes	NGBS
Parent Organization	Environmental Protection Agency	United States Green Building Council	Home Innovation Research Lab International Code Council
Year Established	1995	2008	2008 (Model Green Home Guidelines, 2005)
Benchmark Levels	• Energy Star • Indoor airPLUS	• Certified • Silver • Gold • Platinum	• Bronze • Silver • Gold • Emerald
Rating Categories	• Enclosures •Heating and Cool Equipment •Energy Efficiency •Water Conservation • Indoor Air Quality • Appliances	• Innovation and Design Process • Location and Linkages • Sustainable Sites • Water Efficiency • Energy and Atmosphere • Materials and Resources • Indoor Environmental Quality • Awareness and Education	• Lot Design, Preparation, and Development • Resource Efficiency • Energy Efficiency • Water Efficiency • Indoor Environmental Quality • Operation, Maintenance, and Building
Building Types Certified	• Single-family • Multifamily • Mixed-Use • Major Renovations • Modular Homes • Manufactured Homes	• Single-family • Low-rise multi-family (one to three stories) • Mid-rise multi-family (four to six stories)	• Subdivisions • Single-family • Multifamily • Mixed-Use • Major Renovations • Minor Renovations
Third-Party Verifiers	Home Energy Rater	Green Rater	Green Verifier
System Administrator	Environmental Protection Agency	Green Providers	Home Innovation Research Lab
Certified to Date*	1,799,308	40,291**	109,062

*New and remodeled single-family home, as of July, 2017 (EnergyStar 2017, HIRL 2017, USGBC 2017)

**Total number of projects listed under Homes and Mid-rise Multifamily categories

METHODS

Upon the review of the relevant literature, this study first conducted side-by-side comparisons of LEED and NGBS systems using AIA Cincinnati LEED for Homes/ NGBS comparison (AIA, 2010) as the basis. The Energy Star system was omitted from this comparison due to its limited scope, but serves as an alternate path for the energy performance category in each system. The program requirements for both systems were used to determine the intent of each credit and to match credits in both systems when updating the NGBS requirements. After the credits were matched they were evaluated to determine which phase in project delivery they would be optimally earned in. The evaluated credits were sorted first by performance category and second by phase. The criteria used to evaluate where each of the credits were earned is listed in Table 2.

Table 2: Side-by-Side Comparison Sorting Criteria for Credits

Project Delivery Phase	**Actions Related to Credit Requirements**
Planning & Design	Use of external systems; Preexisting conditions; Coordination; Calculations; Design Deliberations.
Procurement	Purchasing for improved quality
Construction	Preventative activities; Use of alternative construction techniques; Proper installation of materials.
Post-Construction	Inspection and Site testing

Second, the study performed process analyses of the Energy Star for Homes, LEED for Homes, and NGBS. Program requirements of each system and official program documents were gathered. Supporting information about their certification process was downloaded from administering organizations' websites.

Following, expert surveys and interviews were conducted. Three participants for each system, nine builders and nine third-party raters in total, were included in the data collection process. Builders and raters were found using search engines on each of the rating system's parent organization web site and contacted via phone and email. Interviews were first conducted with builders and raters in the mid-Michigan area via face-to-face meetings and phone calls. Upon this first interaction, a survey was developed for data collection. The survey for builders included questions related to documentation requirements, durations, costs, improved quality, participant satisfaction, and general comments. Rater survey focused on project durations, inspection delays, hindrances, up-front costs, and other comments. The digitized surveys were sent to participants via emails. Follow up calls to participants were held as needed. Process flow diagrams for each system were mapped accordingly.

RESULTS

The side-by-side comparison of the LEED and NGBS system credits show that most of the certification credits are earned in the planning and design and procurement phases. This information is useful for builders and owners new to the certification process. It could also be of great assistance to parties that decide to seek certification as an afterthought. If the building design of the project is largely complete, the implementing party can prioritize and focus their efforts by referring to credits that can be earned through procurement or during construction. The full comparison can be found in Jackson (2014).

Sample characteristics for data collection involving human subjects is as follows: Builders from North Carolina and Michigan shared their experience with Energy Star, LEED for Homes and National Green Building Standard. Third-party raters and verifiers from the District of Columbia, Georgia, Michigan, New Jersey, New York, North Carolina, Ohio, and Oklahoma also provided input about their experience with the Energy Star, LEED, and NGBS systems.

Expert Survey & Interview Outcomes: Since parallels existed with regard to a builder's typical customer, builders were grouped together for further analysis of builders serving first-time and move-up buyers.

Builder Input – First-Time Homebuyers: Of the nine respondents, three reported that their typical customers were first-time homebuyers; one Energy Star and two LEED builders. Relative to the respondent pool, builders from the low, mid, and high annual volume cluster groups were represented. The builders in this group were based in Michigan. Of the first-time homebuyer group, two builders developed projects with an element of affordability, and two of the builders had experience certifying over 100 projects. Each builder stated that the use of sustainable practices was a part of their standard building practices and expressed a commitment to green building. Other similarities included experience with only one certification program, the common construction duration of 4 – 6 months, the transfer of all certification related cost to owners, and views that certification improves material installation and quality, but not the quality of customer service.

Builder Input – Move-Up Homebuyers: The remaining six respondents reported that their typical customers were move-up buyers; two Energy Star, one LEED, and three NGBS. Builders from each of the annual volume cluster group were represented. The builders in this group were based in Michigan and North Carolina. Of this group two of the builders had experience certifying over 100 projects where none the remaining four builders exceeded 12 certified projects. Like the first-time homebuyer group, each builder stated that the use of sustainable practices was a part of their standard building practices and expressed a commitment to green building. Other similarities appeared to be consensus based and not consistent among each participant. These similarities included 0 – 6 hours spent on documentation, indifference for sustainable practices from laborers, the use of the homeowner's manual for owner education, and views that certification improves material installation and material quality, but not customer service.

Three notable differences were the varied approach to transferring certification costs, varied owner satisfaction, and the varied experience of encouraging sustainable upgrades. Some builders reported that all of the certification costs were transferred to the owner, while others absorbed some of the costs. Most of the builders in this group reported that customers understood the use of sustainable practices and were aware of the sustainable efforts and satisfied. One builder felt that the owners "often missed the big picture." Finally, builders reported both the willingness and unwillingness of owners to take on additional costs for sustainable upgrades. In some cases, customers that could afford upgrades were easily encouraged when made aware of the return on investment. In other cases, builders found it difficult to encourage upgrades despite the customer's awareness of the potential benefits.

Rater Input: Each of the raters had experience with at least two green building rating systems and each of them had at least five years of experience in sustainable development and certified at least 100 projects. When asked about documentation required by the system, most raters referred the researcher to the system guidelines for an extensive list of submittals required. According to the raters, products with high up-front costs were used in projects depending on the pursued benchmark goals and the time that the rater was brought on. Aside from this, only insulation and energy efficient equipment were cited as having high up-front costs.

When asked what the typical duration of a project was, third-party raters from each system agreed that the project duration is largely dependent on the scale of the project, but is also affected by the benchmark goals, where pursuing higher goals often requires more time and effort. The Energy Star project durations were estimated between 3 to 12 months, whereas the LEED for Homes system was estimated to take at least six months. The NGBS had the longest response estimated for project duration at 8 to 24 months. Two third-party verifiers for the NGBS cited a lack of clarification for program requirements and program submittals. This may explain the lengthy estimates for NGBS project durations.

The time that a project schedule would be extended due to a noncompliant program requirement varied according to the nature of the problem. Several raters stated that efforts are made to avoid extending the project and the completion date is typically not extended due to follow-up inspections. Common hindrances to achieving certification were a lack of communication, misunderstanding program requirements, incorrect installation of materials, noncompliance with general building codes, excessive paperwork, subcontractors that were not invested in the process, negligent builders, and lack of fee payment.

Builder and raters provided varied input about project durations, costs, quality, participant satisfaction, and owner education. Among the nine builders interviewed, the majority of the raters reported to have spent 4 – 6 months constructing a certified green home. When asked if certification costs were transferred to homeowners, builders serving first-time homebuyers reported that they transferred all certification costs. On the contrary, several builders serving move-up buyers reported to have shared some of the costs. Although the builders serving first-time homebuyers did not feel that the certification process improved the quality of their customer service, one of the builders serving move-up buyers felt that it had some positive effect on the service provided their customers.

Several builders expressed that customers appreciated direct benefits such as lower utility bills when asked about customer satisfaction. There was a consensus that most trades were indifferent about their participation in green construction with exception to the trades that benefited from the additional practices required by certification. Each builder had some form of owner education plan, but it was clear that some were more extensive than others. Furthermore, builders that involved customers in the design and certification process seemed to provide the most effective means of owner education. The industry professions interviewed for this research expressed a range of opinions that included frustrations and excitement. Some had strong opinions about the challenges of certification. Many participants expressed frustration about new HVAC requirements that require special training and certification for Energy Star and LEED certification. This new requirement has decreased the pool of eligible HVAC contractors and has put a strain on some markets. Verifiers have also expressed frustration with the lack of clarity in some of the NGBS credits.

Certification Process and Flow: According to the input received from several third-party raters, green building certification proceeds in one of two ways; as forethought or an afterthought. The major difference between these two means of progression is the point at which the third-party rater is engaged. Many of the sustainable practices and techniques used in green building must be incorporated into the design early on. If builders and owners decide to pursue certification as forethought to design, raters are typically engaged early enough to take part in the planning and design process and cost benefit analysis. When engaged during this phase, project owners have the opportunity to utilize the third-party team as a technical resource to optimize the success of the project.

The forethought process flow was used to map the three systems evaluated in this study. Three raters, each having experience with all three systems, were engaged to inform the sequence of the steps of the certification process. Each step and milestone was also identified to occur within one of the four phases identified. Required documentation and the points in which documents are collected is also represented on each diagram.

Process flow maps of Energy Star, LEED, and NGBS certification systems pointed out the similarities for much of the certification processes (Jackson 2014), but revealed major differences in the post-construction phase (Figure 1). Each system uses a different approach to awarding certification. Energy Star certification is verified and awarded by the Home Energy Rater after performance testing. Verification for LEED certification is first forwarded to LEED for Homes Providers for review, and then to the USGBC, before certification is awarded. Green Verifiers submit verification for NGBS projects directly to the Home Innovation Research Lab for review. The time that certification is awarded, is dependent upon the system administrator’s responsiveness and the amount of authority given to third-party raters.

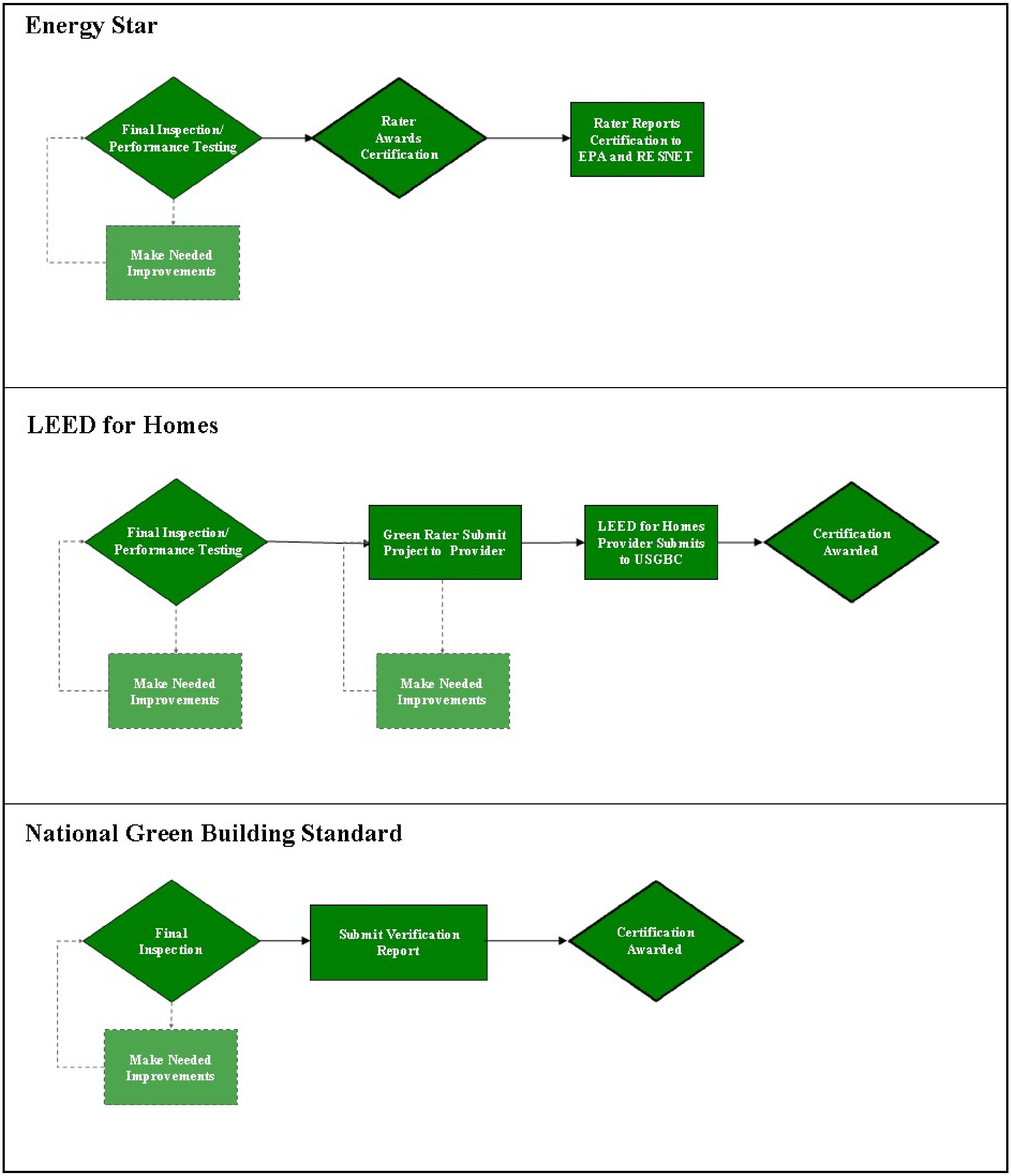

Figure 1: Process Flow Maps for Green Residential Building Certification Process: Post-Construction Activities

DISCUSSIONS & CONCLUSIONS

This study provided an improved understanding of the certification process for Energy Star for Homes, LEED for Homes, and NGBS green residential building rating systems. When considering which system would be the best fit for a new residential building project, the answer is dependent upon several factors that are specific to the project (Figure 2). First, the audience or implementer must be considered. Second, the building type and the type of work may be a determining factor. Third, the implementer's decision may also be a factor of the time at which they decide to pursue certification. Next, the place should be considered to determine the climate as well as the political advantages is disadvantages that the municipality may have. The motivation behind certification may be a strong indication of a decision to select one system over another. The scale of the project and the project's budget is often a primary constraint. Finally, the benchmark level that is pursued may have a major influence on which system is used.

Who

- Municipality
- Builder
- Consumer

What

- Single Family
- Multifamily
- New Construction
- Remodel

When

- Forethought
- After-though

Where

- Climate
- State and Local Regulations
- Incentives

Why

- Stewardship
- Reduced Operation Costs
- Health Benefits
- Higher Quality
- Marketing/ Branding

How Much

- Scale of Project
- Budget

How Green

- Energy Star/ Certified/ Bronze
- Indoor airPlus/ Silver
- Gold
- Platinum/ Emerald

Figure 2: Deciding Factors for Choosing a Green Residential Building Rating System

It is essential that home builders and construction managers in general continue to evolve with innovative green building practices that have proved their value. According to the McGraw Hill (2013) "World Green Building Trends" client demand is the top "trigger driving green building in the future." As the market begins to experience these changes, there will be a need for competent industry professionals. Builders that understand green building rating systems and how they differ from comparable programs will be more prepared. The residential green building model has an emphasis on owner education. Builders will need to be well versed in sustainable practices in order to educate consumers at various points of the client-builder relationship.

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Measuring Sustainability in Low-Energy Residential Buildings

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Abstract

The Applied Economics Office (AEO) of the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST) has extended its metrics and tools for sustainable building products, known as BEES - Building for Environmental and Economic Sustainability (http://ws680.nist.gov/bees), to whole buildings to provide practical metrics, data, and tools to support decisions related to sustainable building designs, technologies, standards, and codes.

Whole building sustainability metrics have been developed based on innovative extensions to life-cycle assessment (LCA) and life-cycle costing (LCC) approaches involving whole building energy simulations. The measurement system evaluates the sustainability of both the materials and the energy used by a building over time. It assesses the "carbon footprint" of buildings as well as 11 other environmental performance metrics, and integrates economic performance metrics to yield science-based measures of the business case for investment choices in high-performance green buildings.

Building Industry Reporting and Design for Sustainability – BIRDS (http://ws680.nist.gov/Birds) – applies these sustainability metrics to three extensive whole building performance databases. Two databases allow for analysis of increased energy efficiency for commercial and residential buildings based on building requirements defined in industry consensus standards (ASHRAE 90.1) and codes (IECC). A 3rd database allows for analysis across energy, economic, environmental, and indoor environmental quality impacts from incremental energy efficiency measures across 10 building components based on a validated model of NIST's Net-Zero Energy Residential Test Facility (NZERTF) in Gaithersburg, MD.

This paper gives an overview of the BIRDS web interface, the data available in the current Low-Energy Residential Database, future data additions to the Low-Energy Residential Database, and a case study using the database to evaluate and compare the sustainability performance of alternative building designs achieving net-zero energy performance to that of a state energy code compliant design.

Keywords

Building economics; life-cycle costing; life-cycle assessment; life-cycle impact assessment; energy efficiency; low-energy buildings; net zero; residential; whole building simulation

1 Overview of BIRDS

1.1 Background

A wave of interest in sustainability gathered momentum in 1992 with the Rio Earth Summit, during which the international community agreed upon a definition of sustainability in the Bruntland report: "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs" (Brundtland Commission 1987). In the context of sustainable development, needs can be thought to include the often-conflicting goals of environmental quality, economic well-being, and social justice. While the intent of the 1992 summit was to initiate environmental and social progress, it seemed to have also brought about greater debate over the inherent conflict between sustainability and economic development (Meakin 1992) that remains a topic of discuss to this day.

This conflict is particularly apparent within the construction industry. Demand for "green" and "sustainable" products and services have grown exponentially over the last decade, leading to 2.5 million "Green Goods and Services" private sector jobs and 886 000 public sector jobs for a total of 3.4 million across the United States. Of these, a million are in the manufacturing and construction industries (Bureau of Labor Statistics 2013). There are nearly 600 green building product certifications, including nearly 100 used in the U.S. (National Institute of Building Sciences 2017), all of which using their own set of criteria for evaluating "green/sustainable." Also, the "green" building segment of the US market has grown 1,700% from market share of 2% in 2005 to 38 % in 2011 (Green America 2013), and was 67% of all projects in 2015 (McGraw-Hill Construction 2017). Projections of green construction spending growth show a rise from $151 billion in 2015 to $224 billion by 2018, leading to total impacts on US GDP of $284 billion (U.S. Green Building Council 2015). Similar trends are occurring internationally as well, with over 100 000 USGBC LEED projects (completed or in progress) and 200 000 LEED professionals in 162 countries (U.S. Green Building Council 2017).

A building's environmental performance is balanced against its economic performance. Even the most environmentally conscious policymaker, building designer, or building owner will ultimately weigh environmental benefits against economic costs. A 2006 poll by the American Institute of Architects showed that 90% of U.S. consumers would be willing to pay up to $5,000 more to reduce their home's environmental impact.[1] More recent studies have shown that U.S. home buyers are willing to pay more for sustainable building designs or homes with green attributes like solar photovoltaics (PV) (Griffin, Kaufman et al. 2009, Hoen 2011, Pfleger, Perry et al. 2011, Aroul and Hansz 2012, Dastrup, Zivin et al. 2012, Kok and Kahn 2012, Kahn and Kok 2014, Adomatis 2015). There are significant variations across locations in the value placed on green-rated homes, which may be driven by consumer preferences or knowledge. To satisfy stakeholders, the green building community needs to promote and design buildings with an attractive balance of environmental and economic performance. These considerations require innovative means to address sustainability performance for buildings (Eichholtz, Kok et al. 2010). Thus, an integrated approach to sustainable construction – one that simultaneously considers both environmental and economic performance – lies at the heart of reconciling this conflict.

1.2 BIRDS

The Engineering Laboratory (EL) of the National Institute of Standards and Technology (NIST) has addressed this high priority national need by extending its metrics and tools for sustainable building

[1] January 2006 survey cited in Green Buildings in the *Washington Post* (Cohen 2006).

products, known as Building for Environmental and Economic Sustainability (BEES) (NIST 2010),[2] at the whole building level in Building Industry Reporting and Design for Sustainability (BIRDS)[3] to address building sustainability measurement in an integrated manner that considers complex interactions among building materials, energy technologies, and systems across dimensions of performance, scale, and time. Whole building sustainability metrics have been developed based on innovative extensions to life-cycle assessment (LCA) and life-cycle costing (LCC) approaches involving whole building energy simulations, and evaluates the sustainability of both the construction materials and the energy used by a building over time. It assesses the "carbon footprint" of buildings as well as 11 other environmental performance metrics, and integrates economic performance metrics to yield science-based measures of the business case for investment choices in high-performance green buildings.

Interest in increasing energy efficiency across the U.S. building stock has been revived in the past decade as fluctuations in fossil fuel prices have increased and an increasing awareness and concern over potential climate change impacts has driven both producers and consumers to decrease consumption from traditional energy sources, either through increasing alternative generation capacity, both at the utility (e.g. wind farms and utility-scale PV – EIA 2017) and household scale (rooftop PV - Barbose and Darghouth 2016) and/or reducing consumption (IEA 2016). Buildings account for 40% of all energy consumed in the U.S., and are "low-hanging fruit" for reducing both energy costs and carbon emissions given the cost-effectiveness of building energy efficiency gains (McKinsey 2017). For this reason, the BIRDS approach considers both the environmental and economic dimensions of sustainability through the lens of increased energy efficiency. BIRDS, however, does not consider the social dimension of sustainability now due to the current lack of applicable rigorous measurement methods.

BIRDS applies the sustainability metrics to an extensive whole building performance database NIST has compiled for this purpose (National Institute of Standards and Technology (NIST) 2014). The energy, environment, and cost data in BIRDS measure building operating energy use through detailed energy simulations, building materials use through life-cycle material inventories, and building costs over time. BIRDS v1.0 included energy, environmental, and cost measurements for 11 building prototypes in 228 cities for a total of 12,540 new commercial and non-low rise residential building designs across all U.S. states for 9 study period lengths.[4] BIRDS v2.0 included both the commercial and residential database that included the energy, environmental, and cost measurements for 9,120 residential buildings, covering 10 single family dwellings (5 one-story and 5 two-story of varying conditioned floor area) in 228 cities for study period lengths ranging from 1 year to 40 years.[5]

Like the previous two databases, the Low-Energy Residential Database initially incorporated into BIRDS v3.0 includes the energy, environmental, and cost measurements. However, instead of considering locations across the country with minimal building design options based on building energy standards and codes, BIRDS v3.0 allows for detailed incremental energy efficiency measure analysis for a single location and study period lengths ranging from 1 year to 40 years. The new low-energy database in BIRDS v3.0 includes 240,000 residential building designs based on the NIST Net-Zero Energy Residential Test Facility

[2] http://ws680.nist.gov/bees
[3] http://ws680.nist.gov/Birds
[4] See Lippiatt, Kneifel et al. (2013) for additional details.
[5] See Kneifel, Lavappa et al. (2016) for additional details related to the underlying assumptions, data sources, and approaches implemented to develop the BIRDS residential database.

(NZERTF) specifications and varying requirements across International Energy Conservation Code (IECC) editions (2006, 2009, 2012, and 2015). The sustainability performance of buildings designed to meet current energy codes can be compared to several alternative building designs to determine the impacts of improving building energy efficiency as well as varying the investor time horizon and other assumptions on overall sustainability performance. See Kneifel et al. (2016) for additional details on the BIRDS v3.0 Low-Energy Residential Database.

BIRDS v3.1 expands the Low-Energy Residential Database by including metrics related to indoor environmental quality (thermal comfort of occupants and indoor air quality) and an additional exterior wall finish option, doubling the building designs to 480,000. In addition to the expansion of the BIRDS Low-Energy Residential Database, the BIRDS interface now includes additional graphing features not available in previous versions of BIRDS. Kneifel et al. (2017) provides additional details on the BIRDS v3.1 Low-Energy Residential Database.

2 BIRDS Low-Energy Residential Database

The metrics available in the BIRDS Low-Energy Residential Database are summarized below, including operating energy, environmental impacts, and life-cycle costs. Kneifel et al. (2017) provides additional details on the BIRDS v3.1 Low-Energy Residential Database.

2.1 Energy Performance

Energy performance for a building is evaluated using annual net energy consumption. The U.S. Department of Energy's EnergyPlus (E+) software was chosen to simulate the whole-building energy performance (U.S. Department of Energy (DOE) 2015).[6] The general assumptions required by E+ are described in detail in Kneifel (2012). Kneifel et al. (2015) documents the validated model for the NZERTF (Figure 2-1) based on the measured performance of the facility over the initial year of demonstration (July 2013 through June 2014), which is the basis for the 480,000 simulations. Assumed operation is based on the weekly narrative defined in Omar and Bushby (2013), which was the basis for operation during the initial demonstration phase. A Typical Meteorological Year 3 (TMY3) weather file for the closest weather station (KGAI) to the NIST campus was used for the simulations (Weather Analytics 2014). The validated model was simplified to allow for a 15-minute timestep instead of the one-minute timestep used in Kneifel et al. (2015) due to the time constraints of simulating 480,000 designs.[7]

[6] Certain trade names and company products are mentioned throughout the text. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is the best available for the purpose.
[7] The policy of the National Institute of Standards and Technology is to use metric units in all its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical to include U.S. customary units as well as metric units. Measurement values in this report are therefore stated in metric units first, followed by the corresponding values in U.S. customary units within parentheses.

Figure 1: The NIST Net-Zero Energy Residential Test Facility

The NIST NZERTF is all-electric operation, and therefore, annual energy consumption equals annual electricity consumption. Electricity production from the 10.2 kW roof-mounted solar PV system assumes a 0.5 % linear degradation rate. The annual electricity consumption and production estimates from the E+ results are used to develop net electricity consumption for each year of operation.

2.2 Environmental Performance

BIRDS uses LCA inventory data and life-cycle impact assessment (LCIA) methods to quantify environmental impacts and link their potential contributions to a range of impact categories. The BIRDS LCIA approach assesses a building design's environmental impact performance using the integrated hybrid LCIA framework developed by Suh and Lippiatt (2012) specifically to allow for whole-building LCA analysis. Process-based LCA systematically estimates detailed environmental inputs and outputs using all non-negligible process flows, which requires time consuming and costly data collection and leads to boundary conditions that truncate some fraction of associated flows. Input-Output (I-O) LCA analysis quantifies proportional interrelationships among economic sectors, which eliminates the boundary conditions by accounting for the entire economy. However, I-O analysis can only be completed at the granularity of the economic sector data. A hybrid LCA approach attempts to combine the best characteristics of the two approaches to improve consistency in system boundary selections and minimizing truncation that results from process-based LCA while accounting for differences between specific building technologies not differentiated in I-O LCA data tables. In the case of a building, it is not feasible given time and budget constraints to develop a process-based LCA for every product installed in a building. At the same time, I-O analysis cannot identify the trade-offs between two building components. The integrated hybrid LCIA framework is applied in BIRDS by combining "top-down" I-O environmental flow data used in estimating the total LCIA flows for a baseline building design, with "bottom-up," processed based data to account for environmental flows associated with changes in individual building components and component combinations (Kneifel, Lavappa et al. 2016).

BIRDS uses environmentally-extended I-O tables for the U.S. construction industry.[8] The "top-down" inventory data is based on the 2007 release of the 2002 BEA I-O data (newest available at the time of development) quantifying 6,204 environmental inputs and outputs occurring throughout production supply chains for the construction sector, which was disaggregated into building type-specific flows per dollar of expenditure for construction, maintenance, and repair (Lippiatt, Kneifel et al. 2013). The environmentally-extended I-O tables classify U.S. construction into 42 distinct industry outputs. Two residential construction industry outputs are used: "residential new construction" and "residential maintenance and repair". For both construction industry outputs, the baseline top-down inventory data are expressed in terms of national average life-cycle environmental flows *per dollar* of construction. For more information on the mathematics, accounting structure, and step-by-step process under which the BIRDS hybrid environmental database is built, see Suh and Lippiatt (2012).

For the bottom-up inventory data on building energy technologies, the most representative technology for which data are available is evaluated using both primary and secondary data sources dependent on the level of disclosure preference by coordinating organizations and companies. The most temporally, technologically, and geographically representative data was selected for each building component based on four types of data sources in descending order of preference: (1) Primary data from a group of companies and/or an industry association, compiled into an industry average product; (2) primary data on a product provided by one company; (3) secondary data that represent an average or typical product; and (4) secondary data that represent one product in a category. Background data sources are primarily the U.S. LCI database and Ecoinvent v2.2 database (Kneifel, Lavappa et al. 2016). All building component process-based LCA data are in terms of flow per functional unit of the specific component and are based on national inventory data. Electricity production inventory data applied to a building's use of electricity to convert site flows to source flows are based on 2008 eGRID data from NERC sub-regions.

In the BIRDS model, the functional unit is construction and use of a building prototype over a user-defined study period. A residential building lifetime is assumed to be 65 years, longer than the 30-year study period considered in this study. Therefore, 100% of each building is "recycled" at the end of the study period and there are no end-of-life waste flows allocated to the building at the end of the study period. Rather, end-of-life waste flows should be allocated to a different "product," representing use of the building from the end of the study period to the end of the building service life. Similarly, the environmental burdens from building construction are allocated only to its first use (equally distributed across each year of the selected study period). This effectively credits the use of existing buildings over new construction and ensures there will be no double counting if the framework is applied to existing building LCA analysis (Kneifel, Lavappa et al. 2016). The equal distribution of construction flows across each year of a building's service life, or annualized flow approach, is a common practice (Hannon, Stein et al. 1978, Zimmermann, Althaus et al. 2005, Hernandez and Kenny 2008, Blengini and Di Carlo 2010, Hernandez and Kenny 2010) in building-related LCA evaluation.

Annualization allows for relatively straightforward comparison of embodied and operating flows independent of the selected study period because the flows associated with the initial construction are allocated across its service life instead of at the time of construction. This allows for a long-term environmental impact perspective while allowing BIRDS users to select a shorter study period that aligns with their desired investment time horizon. Treating the construction flows as "sunk" at the beginning of the study period will lead to embodied flows accounting for much larger fractions of overall flows than is the case for longer study periods, which can skew interpretations of the energy and environmental trade-

[8] Developed under contract to NIST by Industrial Ecology Research Services of Goleta, California

offs of greater energy efficiency. Building components that have a different service life than the building itself (e.g. heating and cooling systems) use the same annualized approach based on their specific service life.

2.3 Economic Performance

The most appropriate method for measuring the economic performance of a building is life-cycle costs (LCC) (Fuller and Petersen 1996, ASTM 2012). BIRDS follows the ASTM International standard method for LCC of building-related investments (ASTM 2010), which involves calculating a present value of all costs of construction, operation, maintenance, repair, and replacement, and residual value related to the building over the selected study period. Total life-cycle costs of a building (C_{LCC}) is the sum of the present values of first cost and future costs minus the residual value for a given study period and assumed discount rate as shown in equation (1):

$$C_{LCC} = C_{First} + C_{Future} - C_{Residual} \tag{1}$$

First costs (C_{First}) are realized in Year 0 and include all the costs associated with constructing a building, such as contractor labor, materials, equipment, overhead, and profit.[9] Future costs (C_{Future}) include all costs realized after Year 0 throughout the study period, and include the present value maintenance, repair, and replacement (MRR) costs (C_{MRR}) as well as present value operating energy-related costs of energy consumption (C_{Energy}) based on location-specific energy prices and projections, as shown in equation (2):

$$C_{Future} = C_{MRR} + C_{Energy} \tag{2}$$

For some building designs in the database, a building exhibits negative annual energy consumption resulting from the combination of lower energy consumption from energy efficiency measures and electricity production from the solar PV system. Based on a local utility's rate schedule, the estimated cost of consuming electricity including all charges, taxes, and fees is assumed to be 14.0¢/kWh (average cost) while the value of excess production is assumed to be 8.4¢/kWh, which is the generation charge for one kWh of electricity (PEPCO 2017).

Electricity prices are assumed to change over time according to U.S. Energy Information Administration (EIA) forecasts from 2015 to 2045 (U.S. Energy Information Administration (EIA) 2015). These forecasts are embodied in the U.S. Department of Energy's Federal Energy Management Program (FEMP) Modified Uniform Present Value Discount Factors (UPV*) for energy price estimates reported in Lavappa and Kneifel (2015).[10]

The residual value component of total life-cycle costs ($C_{Residual}$), is remaining value of the building at the end of the study period. In life-cycle costing it is treated as a negative cost item. In BIRDS, it is estimated in two major parts based on the approach defined in Fuller and Petersen (1996): the building excluding components that get replaced, and the building components that get replaced (HVAC, DHW, solar thermal system, solar photovoltaic system, windows, and lighting). The building's residual value is calculated as the building's first cost (excluding HVAC, DHW, solar thermal, solar photovoltaic system windows, and lighting costs) multiplied by one minus the ratio of the study period to the service life of the building, discounted from the end of the study period for the last year of the study period (T).

[9] Does not include closing costs, such as realtor commissions.
[10] Since the U.S. Energy Information Administration forecasts end at year 30, the escalation rates for years 31 through 40 are assumed to be the same as for year 30.

The following section provides details on a case study illustrating how the BIRDS Low-Energy Residential Database can be used to evaluate and compare the sustainability performance of alternative building designs achieving net-zero energy performance to that of a state energy code compliant design.

3 Case Study – Maryland State Code versus Cost-Optimal Net Zero

The BIRDS interface can be used for a range of purposes when using the Low-Energy Residential Database, including identifying key building designs that meet certain goals (e.g. minimize life-cycle costs) and comparing the performance of these key design across a range of sustainability metrics, comparing different IECC editions, and analyzing the impacts of incremental efficiency improvements to a specific building component (e.g. windows). This case study will focus on comparing the performance of a house based on the NZERTF, but built to meet Maryland code requirements (2015 IECC), to higher efficiency building designs based on combinations of building components using current Maryland code requirements and the specifications of the NZERTF.

3.1 BIRDS Software Process – 4 Easy Steps

After selecting the Low-Energy Residential Database "Start Analysis >>" on the BIRDS main webpage, the user is directed to the Low-Energy Residential Database web interface. The user follows a 4-step process in making comparisons:

1. Step 1: Select your general assumptions, location, and baseline building design.
2. Step 2: Select alternative building components to be compared to the baseline building design.
3. Step 3: Select weighting preferences for environmental performance.
4. Step 4: View results graph(s) and data.

3.1.1 Step 1: Selecting Your Baseline Assumptions

The user completes the first part of "Step 1: Select Your Baseline Assumptions" by selecting the assumptions to be used in the analysis from the seven drop-down menus shown in Figure 2-2. Selections are made based on the preferences of the user. There are several assumptions that currently only offer one option: Building Type (**NZERTF**), State (**Maryland)**, and City (**Gaithersburg**). Two options are available for Discount Rate (**3%** and **8%),**[11] Financing (**Cash Only** and **80/20 loan financing**), Construction Quality (e.g., architecture and finishes) (**Average** or **Luxury**), and Exterior wall finish (**wood siding** or **brick veneer**). The user can select a Study Period between **1 year** to **40 years** in one year increments. The user must also select the components of the baseline building, which could be an edition of IECC or a custom design based on a combination of the 10 building component options: Wall, Attic, Window, Foundation Wall, Foundation Floor, Lighting, Air Leakage, Heating, Cooling, and Ventilation (HVAC), Domestic Hot Water, and Solar photovoltaic. For this case study, the Maryland code-compliant design (2015 IECC) is the assumed baseline. The following values are the remaining selected assumptions: **8%** discount rate, loan with 20% down payment (**80/20**) financing, **Average** construction quality, and a **30-year** study period.

3.1.2 Step 2: Selecting Your Comparisons

Step 2 requires the user to select the alternative building component combinations to compare to the baseline design, which can include editions of the IECC or custom designs and could include all 240 000 available options as shown in Figure 2-2. All combinations of the baseline building components and the alternative

[11] These two options were selected to represent two different investment alternatives, 3% for individuals that would investment in a less risky asset such as treasury bills and 8 % for those that would investment in riskier asset such as stocks. Additional options will be added in future updates of BIRDS.

component selections will be reported. For example, if a user selects “Foundation Wall” = **R-22** and “Solar PV” = **10.2 kW** as alternatives, then BIRDS will report results for

(1) the baseline building as defined (foundation insulation of R-10 and no solar PV system)
(2) baseline building with ONLY the foundation insulation increased to R-22
(3) baseline building with ONLY the 10.2 kW solar PV system added to the roof
(4) baseline building with BOTH the foundation insulation increased to R-22 and the solar PV system added to the roof

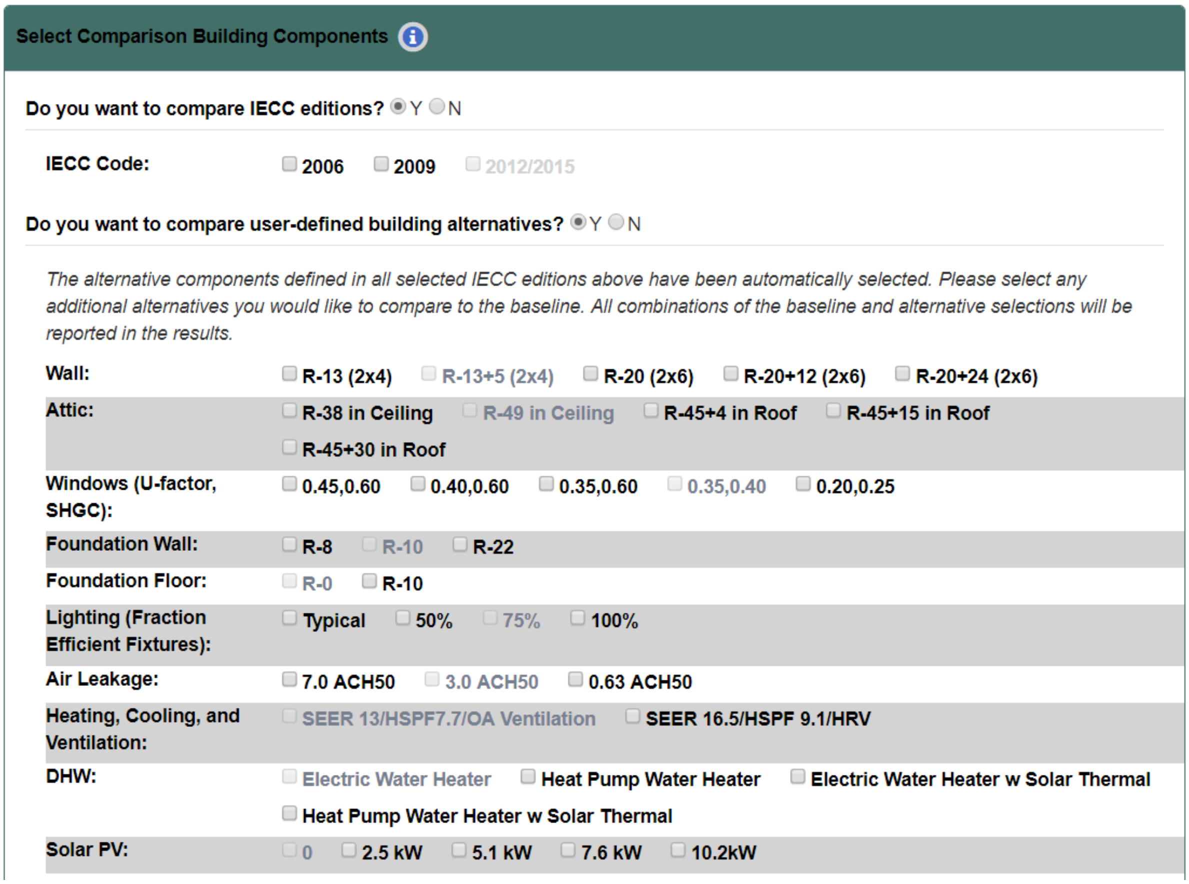

Figure 2: Summary Tables

For this case study, assume that the user is interested in comparing the NZERTF design to current Maryland code requirements. The user must select the most efficient option for each building component: Wall = (**2x6** wall assembly) with **R-20+24** insulation, Attic = **R-45+30 in Roof**, Windows = **0.20,0.25**, Foundation Wall = **R-22**, Foundation Floor = **R-10**, Lighting = **100 %**, Air Leakage = **0.63 ACH50**, Heating, Cooling, and Ventilation = **SEER16.5/HSPF 9.1/HRV**, DHW = **Heat Pump Water Heater w/ Solar Thermal**, and Solar PV = **10.2 kW**. BIRDS will report the results for all combinations of the baseline characteristics selected in Step 1 and Step 2, allowing for incremental analysis of each building component option selected.

3.1.3 Step 3: Selecting Environmental Weighting Preferences

Step 3 requires the user to specify their environmental preferences, which specifies how important each environmental impact category is to the user. A user can either select one of the pre-defined weighting approaches or create their own. Should the user choose to create their own series of weights, they must assign a weight ranging from 0 to 100 to each of the 12 impact categories with the sum totaling 100. For this tutorial, assume the user prefers the EPA Science Advisory Board weighting approach.

3.1.4 Step 4: Viewing Results

Step 4 provides the user with five options to view the results: **Download Data**, **Summary Table**, **Scatter Plots**, **Radial Charts**, and **Line Charts**.

The results are defaulted to the **Download Data** tab, which allows BIRDS users to download all results data for all selected building design options in CSV format (BIRDSRawData.txt) for conducting their own analysis, such as comparisons that cannot currently be displayed in BIRDS' graphing features.

The **Summary Table** tab displays two tables of data (screenshot shown in Figure 2-3). The top table displays the building characteristics for up to 6 key building designs from the subset selected in Step 1 and Step 2 above, and are defined as follows:

A = baseline design.
B = design that leads to the lowest LCC
C = design that leads to the lowest energy consumption for the same LCC as the baseline design
D = design that reach net-zero energy performance at the lowest cost
E = design that reach the lowest energy consumption
F = design that leads to the lowest EIS

The bottom table displays the reported sustainability performance metrics for each of the key building designs defined above: LCC, initial investment cost, percentage change in energy consumption, percent change in EIS, percent change in climate change potential, hours not comfortable, hours CO_2 above 750 parts per million (ppm), and hours CO_2 above 900 ppm.

The results in Figure 2-3 show that the most cost-effective building design lowers LCCs by $7,696 while decreasing net energy consumption by 23.5%, climate change potential by 11.5%, and the Environmental Impact Score (weighted-average of all impact categories) by 10.6% relative to the 2015 IECC design, respectively, by installing more efficient windows, using 100% efficient lighting, and reducing air leakage. By adding the solar thermal and solar photovoltaic systems to the minimum LCC design, net-zero energy performance is achieved (100.1% reduction in net energy consumption), but at additional LCC of $5,419. The maximum reduction in net energy consumption (118.6%) and EIS (70.4%) are realized by the same design, which increases LCC by $23,008. Also, decreasing air leakage decreased the number of hours occupants are considered uncomfortable while increasing the hours for which the CO_2 levels are above the two thresholds (750 ppm and 900 ppm), implying a potential trade-off between comfort and indoor air quality and a greater need for minimizing sources and levels of pollutants within the house.

Characteristics of Key Building Designs

Description	ID	Wall	Attic	Windows	Foundation Wall	Foundation Floor	Lighting	Air Leakage	HVAC	DHW	PV
Baseline	A	R-13+5 (2x4)	R-49 in Ceiling	0.35,0.40	R-10	R-0	75%	3.0 ACH50	SEER 13/HSPF7.7/OA Ventilation	Electric Water Heater	0
Min Life-Cycle Costs	B	R-13+5 (2x4)	R-49 in Ceiling	0.20,0.25	R-10	R-0	100%	0.63 ACH50	SEER 13/HSPF7.7/OA Ventilation	Electric Water Heater	0
Min Energy Consumption at Baseline LCC	C	R-20+24 (2x6)	R-49 in Ceiling	0.20,0.25	R-10	R-0	100%	0.63 ACH50	SEER 13/HSPF7.7/OA Ventilation	Heat Pump Water Heater w Solar Thermal	0
Net Zero	D	R-13+5 (2x4)	R-49 in Ceiling	0.20,0.25	R-10	R-0	100%	0.63 ACH50	SEER 13/HSPF7.7/OA Ventilation	Heat Pump Water Heater w Solar Thermal	10.2kW
Min Energy Consumption	E	R-20+24 (2x6)	R-45+30 in Roof	0.20,0.25	R-22	R-0	100%	0.63 ACH50	SEER 16.5/HSPF 9.1/HRV	Heat Pump Water Heater w Solar Thermal	10.2kW
Min EIS	F	R-20+24 (2x6)	R-45+30 in Roof	0.20,0.25	R-10	R-0	100%	0.63 ACH50	SEER 16.5/HSPF 9.1/HRV	Heat Pump Water Heater w Solar Thermal	10.2kW

Results for Key Building Designs (visually shown in the Radial Charts tab)

Description	ID	LCC ($)	Initial Investment Cost ($)	% Change in Energy Consumption	% Change in EIS	% Change in Climate Change	Hrs Not Comfortable	Hrs CO2 > 750 PPM	Hrs CO2 > 900 PPM
Baseline	A	254,280	68,820	0	0	0	622	319	16
Min Life-Cycle Costs	B	246,584	68,995	-23.5	-10.6	-11.5	552	1,699	907
Min Energy Consumption at Baseline LCC	C	253,825	72,559	-39.2	-16.6	-11.5	464	1,705	907
Net Zero	D	259,699	78,408	-100.1	-10.6	-11.5	538	1,691	886
Min Energy Consumption	E	278,788	86,061	-118.6	-48.3	-70.4	91	1,744	955
Min EIS	F	277,288	85,532	-118.6	-48.3	-70.4	92	1,753	954

Figure 3: Summary Tables

The **Scatter Plots** tab can be used to view scatter plots that compare the life-cycle cost and initial investment costs to energy savings for two series of data, the key building designs shown in the **Summary Table** tab (**Key Points**) and the complete set of building designs selected in Step 1 (**All Selected Points**) and Step 2. These comparisons allow a user to visualize how the LCC changes as energy savings is increased for the subset of building designs selected by the user. Additionally, the user can see how much additional investment cost the user must pay upfront to obtain that energy savings. Figure 2-4 shows that a 39.2% reduction in energy savings can be obtained for the same LCC as the baseline design (furthest left yellow point). There is a clear clustering of data points to the left and right of 60% energy reduction because the installation of the 10.2 kW solar photovoltaic system leads to large reductions in net energy consumption but at a significantly higher cost.

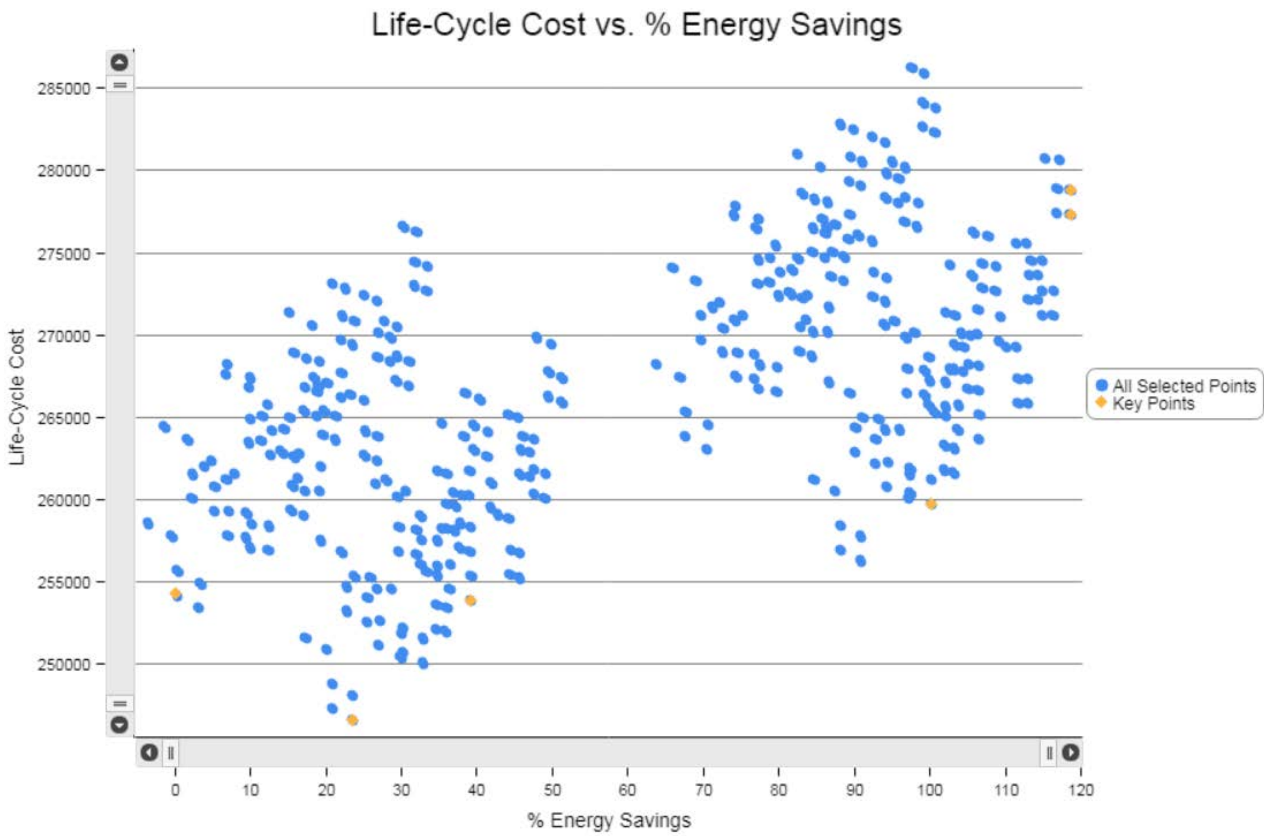

Figure 4: Scatter Plot

The **Radial Charts** tab displays radial charts for two series of data, the metrics displayed in the **Summary Table** tab and the 12 environmental impact categories. The radial charts give an easier to interpret visual comparison for each of the metrics considered in the **Summary Table** tab. Figure 2-5 shows the environmental impact category results as a percentage of the baseline building design value. As the energy consumption decreases, so does **Climate Change**, **Smog**, and **Acidification** impact category results due to the reduction in energy-related emissions, with the greatest reductions occurring for **Climate Change** (70.4%). However, some of the individual environmental impact category results are worse for the more efficient building designs. The greatest percentage change for the **Net Zero** design is in **Ecotoxicity** driven primarily by the heavy metals in the solar PV system. Significant increases are also realized in **Eutrophication**, and **Non-carcinogenic** human health effects.

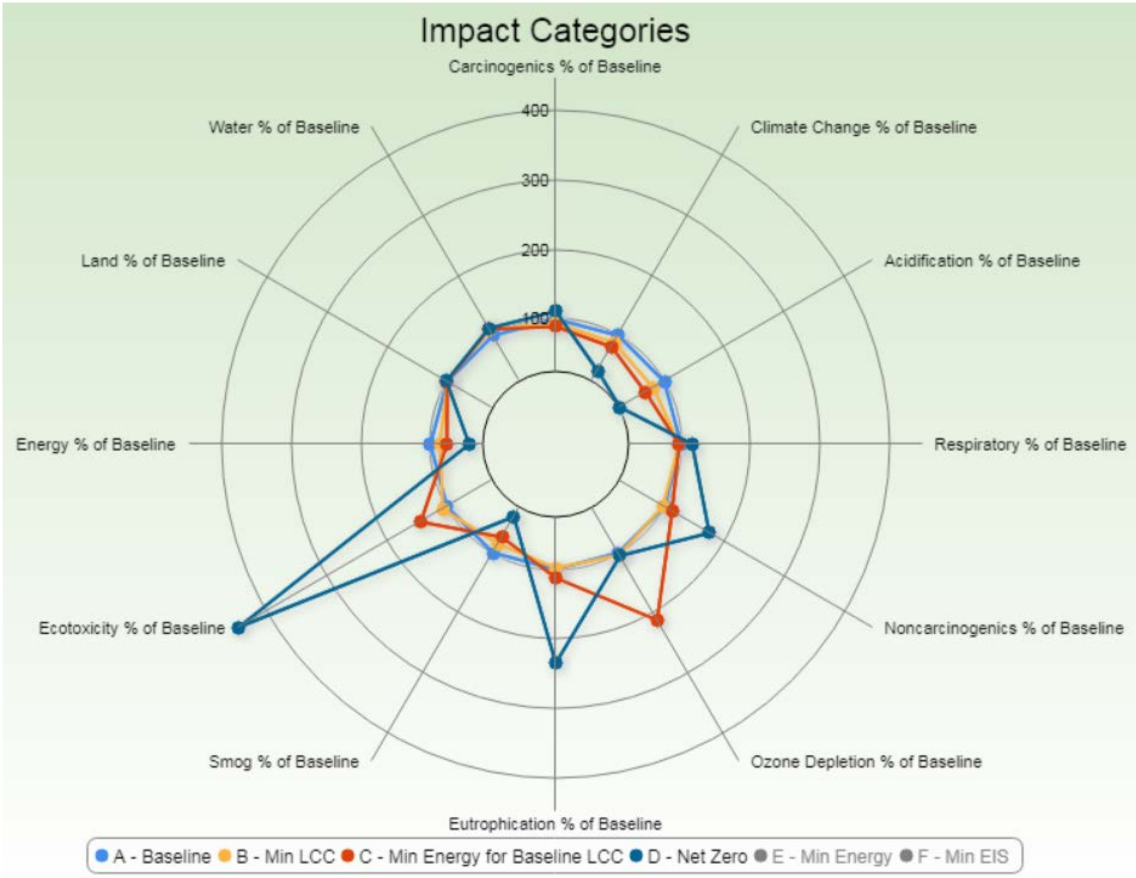

Figure 5: Radial Chart – Environmental Impacts

4 Discussion and Future of BIRDS

By using BIRDS, a user could compare the sustainability performance (energy, economic, and environmental) of reaching and exceeding net-zero energy performance relative to constructing to current Maryland state residential building energy codes. Under the selected economic assumptions (8% discount rate and 80/20 loan), increased energy efficiency (26%) and lower environmental impacts (10.6%) can be obtained relative to the current Maryland residential building code, which is based on 2015 IECC, at lower life-cycle costs to the homeowner over a 30-year study period. Even greater energy savings can be achieved (39%) for the same life-cycle costs as the Maryland-code compliant design. Reaching net zero energy performance is not yet cost-effective due to the significant additional costs associated with installing the solar photovoltaic system, but only increases life-cycle costs by $5,419. The greatest reductions in net energy consumption (118.6%), Climate Change Potential (70.4%), and EIS (48.3%) are achieved by a building design that increases life-cycle costs by over $23,000. The EIS value is reduced by significantly less than Climate Change Potential because other impact categories (e.g. **Ecotoxicity**) realize increased environmental impacts, which emphasizes the importance of considering all LCIA impact categories in sustainability analysis of whole buildings. Additionally, greater energy efficiency through reductions in air leakage improve thermal comfort while increasing the potential for indoor air quality concerns, implying a need for more attention towards minimizing sources and levels of pollutants within the building.

The ability to customize user assumptions and preferences means that the results of the analysis above could change, which emphasizes the power and capabilities of BIRDS to assist users in making informed decisions under their specific situation. BIRDS can assist in answering an array of questions related to the sustainability performance of buildings as related to building energy efficiency.

Plans for the next version of BIRDS (v4.0) will include an update to all three databases and associated web interfaces. The updated commercial database will include new prototypes based on the Pacific Northwest National Laboratory's Commercial Prototype Buildings, while its interface will be updated to be consistent with the other web interfaces. The residential database will be updated with new building cost data and be designed to easily incorporate results for new editions of IECC. The Low-Energy Residential Database will add multiple natural gas space and water heating equipment options and a 12.4 kW solar PV system. Along with expanding the capabilities and features in BIRDS, the BIRDS framework has also been used to develop a new software tool (BIRDS NEST – Neutral Environment Software Tool) to assist building designers in their evaluation of the environmental performance of custom buildings created in the Department of Energy's OpenStudio application, which is currently available in a beta version at OpenStudio's Building Component Library (BCL).

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Is Green Housing Healthy Housing: Examining the Evidence

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ABSTRACT

For many in the housing industry and in the general public, "green design and construction" may seem to also reflect building performance for occupant health. A 2006 report of research conducted by the National Center for Healthy Housing demonstrated, however, that this was not necessarily a safe assumption. This paper presents research that expands and updates that earlier 2006 research, by examining the extent to which today's green building certification programs for residential structures achieve a building performance that maximizes a healthy living environment for occupants. Two national health-related building certification standards – WELL and National Healthy Housing Standard – represent benchmark resources for identifying health-related design and building measures for multifamily residential. Our analysis examined the correspondence of the health provisions of these two standards with design, construction, operations and management measures of two green certification programs for housing: LEED for Homes (version 4) and Enterprise Green Communities 2015 Criteria. Results of this correspondence are described for: biological contaminants in indoor air quality (IAQ), chemical contaminants in IAQ, and ventilation. The results indicate that these green building programs address a segment of health-related occupancy concerns, but are far from being as comprehensive as the health-related housing certification standards. In a few instances, possible conflicts between green programs and healthy housing guidelines may actually exacerbate or compromise occupant health. The paper ends with suggestions for advancing a healthier housing stock in light of green building programs.

INTRODUCTION

The past two decades has produced a steady stream of green buildings (Dodge Data & Analytics, 2016). Recently developers, architects and builders have expressed interest in producing a healthier building stock as well, one that goes beyond conventional health and safety codes (McGraw Hill Construction, 2014). There is considerable research documenting the built environment's impact on occupant health and performance, targeting buildings' indoor air quality, natural and artificial lighting, thermal conditions, ventilation, building materials, and the like (e.g. (Ahrentzen, Tural, & Erickson, 2017; Jacobs, 2009; Krieger & Higgins, 2002;

Krieger et al., 2010; Matte & Jacobs, 2000; WHO, 2006). Yet, where does the building industry turn for guidance in producing a building stock more responsive to occupant health? For many, "green design" and "health" seem synonymous. But environmental health scientists demonstrate that while the two sometimes correspond, they also can conflict (Allen et al., 2015; Wargo, 2010). For example, initial green building efforts towards producing extremely tight building envelopes with minimal indoor-outdoor air exchange sometimes resulted in intensified exposures to indoor toxins and subsequent respiratory problems.

In 2006, the National Center for Healthy Housing, or NCHH , produced a report that compared five green building certification programs with five healthy homes principles, allowing housing developers, architects and builders to gauge the health responsiveness of different green programs (Mermin, Morley, Powell, & Tohn, 2006).

Much has happened in the last ten years since that report: the number of green building certification programs has grown, their scope and sophistication has expanded, and health-related building certification programs have been developed. Our analysis in this paper updates and expands upon the earlier work of the NCHH report. In this paper, we focus on green design as covered in two green certification programs used in the U.S. for residential structures. We have chosen to focus exclusively on residential structures since those are settings where people spend much of their lives, and also where the most vulnerable populations – young children, older adults, infirmed – spend most of their time (Berry, 1991; Cohen-Hubal et al., 2000; Tsang & Klepeis, 1996).

We do not cover here the extensive body of research on health-related impacts of residential indoor building factors. That can be found in other sources, such as those identified above. Suffice to say here that research has documented associations between indoor residential factors and numerous health conditions, including stress and depression (due to housing quality, household density and crowding, noise); cardiovascular disease (from VOCs, sedentary behavior); lung cancer (from radon); neurological disorders (from lead); chronic respiratory diseases including asthma (from pests, animal dander, environmental tobacco smoke, humidity, heat, dust mites); infectious diseases (poor sanitation and hygienic conditions); mortality (excessive heat or cold); injuries such as falls or scalds (from hazards, fixtures); and obesity and its related illnesses such as diabetes (from environmental factors that support sedentary behavior).

This paper first describes two national health-related building certification standards – WELL and National Healthy Housing Standard (NHHS). We then describe the protocol of our research analysis. The results section displays the extent to which two green certification programs reflect, neglect or even potentially contradict the health-related building standards in WELL and NHHS. The paper ends with concluding remarks of lessons learned from the analysis.

DESIGN/CONSTRUCTION GUIDELINES FOR HEALTHY HOUSING

While building and housing codes address some of the egregious building factors that can threaten health and safety – such as evenness of stair treads or lead-free paint – existing codes often do not include comprehensive health responses, nor address more chronic health conditions such as maintaining dry environments to reduce mold and mildew that exacerbate asthma. According to the Centers for Disease Control and Prevention (n.d.), "a healthy home is sited, designed, built, renovated, and maintained to support health. A healthy homes approach is a coordinated, comprehensive, and holistic approach to preventing diseases and injuries that result from housing-related hazards and deficiencies." Accordingly, we use the term *"healthy housing"* in this paper to reflect evidence-based design and building factors that have been shown as conducive to resident health.

Two recent initiatives have produced residential building and design provisions that contribute to occupant health, or healthy housing. Developed by the National Center for Healthy Housing (NCHH) and the American Public Health Association (APHA), the *National Healthy Housing Standard* (herein referred to as NHHS) is an evidence-based tool to improve housing conditions related to occupant health as they pertain primarily to housing renovations (National Center for Healthy Housing and American Public Health Association, 2014). This U.S. standard is a modified version of one produced by the UK government, *Housing Health and Safety Rating System* (Department for Communities and Local Government, 2006). NHHS addresses: duties of owners and occupants; structures, facilities, plumbing, and space requirements; safety and personal security; lighting and electrical systems; thermal comfort, ventilation and energy efficiency; moisture control, solid waste, and pest management; and chemical and radiological agents.

The NHHS includes both minimum building performance provisions and those it calls "stretch," the latter including provisions that may be difficult to achieve due to cost or feasibility. The NHHS was intended to place modern public health information into housing code language.

The second health-related building standard is one developed by the International WELL Building Institute (2015), a pilot version (as of this date) for multifamily residential (herein referred to as "WELL"). Provisions in this standard are intended to benefit cardiovascular, digestive, endocrine, immune, integumentary, muscular, nervous, reproductive, respiratory, skeletal, and urinary systems. According to its document, the WELL Building Standard was developed by integrating scientific and medical research and reviewing existing literature on environmental health, behavioral factors, health outcomes and demographic risk factors.

The WELL standard is organized into seven categories of wellness: Air, Water, Nourishment, Light, Fitness, Comfort, and Mind. Similar to the two-tier system of NHHS, WELL features are designated as either preconditions (i.e. they must be met), or optimizations (i.e. encouraged to gain higher levels of certification). Unlike NHHS, WELL targets both new construction and renovation.

While there is some overlap between the two standards, each also addresses unique health-related building concerns, or addresses a particular health concern in more depth than the other standard does. As a result, our analyses of two green certification programs were based on their correspondence with occupant health-based standards in both NHHS and WELL.

PROTOCOL

The purpose of our study was to gauge the level of correspondence between the health-related building provisions of the standards identified above (WELL and NHHS) with green certification programs for residential design and construction. For the latter, we examined LEED Reference Guide for Homes Design and Construction version 4 (USGBC, 2015) and Enterprise Green Communities 2015 Criteria and Certification (Belzer et al., 2015). (Hereafter, these are referred to as LEED and EGCC respectively.). For LEED, we considered both Design and Construction (HD+C) and Operations and Maintenance (O+M). LEED is well known among the design and building industry, as well as having brand recognition among the general public. While not used as extensively as LEED, Enterprise Green Communities targets the affordable housing industry and has made concerted efforts to incorporate health-related factors in its green certification program.

The first step of our protocol was to develop a common nomenclature for the different terms used in the various programs and standards. What was "required" in one program, could be labeled as "precondition" or "mandatory" or "minimum" in another. Table 1 lists the terms we used for consistency across programs.

The second step involved listing each single health provision of WELL and NHHS. When a single provision in NHHS contained sub-provisions, we folded the latter sub-provisions into the single provision since the sub-provisions tended to address details of the larger provision. WELL did not have sub-provisions but rather separate "parts" of a Health provision. These parts reflected different aspects of the overarching provision. As such, we listed each part as a separate provision. For our analyses in this paper (pertaining to Biological Contaminants, Chemical Contaminants, and Ventilation), this included 45 required and 14 optional NHHS health provisions, and 36 required and 38 optional WELL health provisions.

While WELL and NHHS organized their provisions into different overarching categories (as described in the previous section), to maintain a level of consistency in our analyses, we then grouped the provisions of each HR Standard into one of six general categories: (1) Biological Containments in IAQ; (2) Chemical Contaminants in IAQ; (3) Ventilation; (4) Thermal Conditions; (5) Water; and (6) Lighting. For this paper, we are reporting on only the first three of these categories.

Table 1. Definition of Terms Used in Study

Term Used in Study	Definition
HR (health-related) Standard	The entire package of provisions incorporated in WELL and NHHS
Green Certification Program (GCP)	The entire package of measures used in the rating systems of LEED and EGCC
HR Category	Our grouping of provisions in the HR Standards that reflect (1) biological contaminants in IAQ; (2) chemical contaminants in IAQ; or (3) ventilation
Health Provision Type	Within each HR Category, provisions grouped together that represent similar health-related response (e.g. in Biological Contaminants Category, provision types include pest management, moisture prevention, solid waste, etc.).
Health Provision	A single design/construction criteria within the HR Standard
Green Measures	A single design/construction or operations/maintenance criteria used in the rating systems of LEED and EGCC
Required	Identified in the HR Standard or Green Certification Program as mandatory, minimum, precondition, prerequisite
Optional	Identified in the HR Standard or Green Certification Program as optional, optimization, stretch or credit

After listing the Health provisions for each category in separate Excel worksheets (one for WELL, one for NHHS) and indicating whether the provision was required or optional, we then examined each of the green measures in LEED and EGCC to determine if it corresponded with any of the Health provisions. If so, on the worksheet we indicated next to the provision the specific green measure corresponding to it, and whether the green measure was (a) required or optional, and (b) whether the green measure fully met or only partially met the Health provision as stated. We assembled this data in an extensive multi-matrix format (see Table 2 as an example) to use as the foundation for our analyses and interpretation, which follows below.

Table 2. Example of Data Collection Matrix Used for Identifying Correspondence between Specific Health Provisions and Green Measures

NHHS Biological Contaminant Provisions	HR R/O	LEED D+C	LEED O+M	R/O	F/P	EGCC	R/O	F/P
2.4 Kitchen floor sealed, water resistant, nonabsorbent, cleanable surface	R	--	--	--	--	6.8	R	F
Etc.								

RESULTS

As mentioned earlier, while our analyses covered six categories associated with healthy housing conditions, this paper reports only three (because of space limitations): biological contaminants in IAQ, chemical contaminants in IAQ and ventilation. These are described below.

Biological Contaminants in IAQ

Common sources of biological air contaminants include, but are not limited to: animal dander; fungi and molds; some infectious agents (e.g. Legionella); pollen from surrounding plants; mites, cockroaches and other common indoor pests and their excretions. Contaminants can enter the home through: air infiltration and filtration systems; transmission by shoe soles of humans, paws of pets, and the like; dampness in basements and bathrooms; and rodents and other pests (Krieger, et al., 2010).

Among the health provisions addressing biological contaminants, NHHS had 16 required provisions, 5 optional, while WELL had 9 required and 10 optional.

Table 3 shows the correspondence between WELL and the two green certificate programs. WELL included a range of provisions to prevent biological contaminants, encompassing the building's design, building and interior materials, and environmental systems. As seen in Table 3, required moisture management health provisions are covered fairly well as required measures in EGCC, although not so in LEED. But microbial and mold control health provisions are partly covered as required LEED HD+C measures, but not at all by EGCC. Required WELL cleaning protocol (i.e. a specific cleaning plan for occupied spaces) is not addressed in either WELL or LEED, including LEED O+M where it might likely be located. WELL's Healthy Entrance provision type includes two provisions: permanent entryway walk-off system, and entryway air seal. LEED addresses the permanent entryway walk-off but as an optional measure, not required. The optional health provisions of WELL are rarely addressed by either green certification program. Notably, WELL's air infiltration management provision that includes leak tests by blower door testing, infrared thermography or hot wire anemometer is optional, but is required by EGCC.

Table 4 shows the correspondence between NHHS and the two green building programs for biological contaminant provisions. EGCC, LEED HD+C and LEED O+M address some, but not all, of the five provisions covering Pest Management. For EGCC and LEED HD+C, the measures are required, as in this particular health provision type. Moisture Prevention and Control, however, is covered minimally (2 of 8 provisions) by EGCC, and those two are optional. The Kitchen provision encompasses a floor in good condition with a sealed, water-resistant, nonabsorbent, and cleanable surface; which is fully required by EGCC but not by LEED. Notably, Solid Waste provisions are not considered at all by the green programs (these provisions identify containers of trash and of recyclables in terms of capacity and placement). The optional health provisions for Solid Waste and Moisture Prevention and Control are not addressed by LEED. But three of the four optional provisions for Moisture Prevention are addressed by EGCC, one as required and the other two as optional.

Table 3. Correspondence between WELL and Green Certificate Programs on Biological Contaminant Provisions

Biological Contaminants

Health Provisions	Green Certification Program		
WELL	**EGCC 2015**	**LEED v4 HD+C**	**LEED v4 O+M**
Required Provisions			
Microbe + Mold Control	○○	◒◒	○○
Healthy Entrance	○○	◍○	○○
Cleaning Protocol	○	○	○
Moisture Management	●◒◒○	○○○○	○○○○
Optional Provisions			
Air Infiltration Management	●	◡	○
Humidity Control	○	○	◡
Pest Control	○○	○○	◡○
Advanced Air Purification	○○	○○	○○
Antimicrobial Surfaces	○	○	○
Cleanable Environment	◒◡	○○	○○

Key: Health provision requirements are ...

● ◍ ○ met by required, optional, or not met by GCP measure

◒ ◡ partly met by required, or optional, GCP measure

Table 4. Correspondence between NHHS and Green Certificate Programs on Biological Contaminant Provisions

Biological Contaminants

Health Provisions	Green Certification Program		
NHHS	**EGCC 2015**	**LEED v4 HD+C**	**LEED v4 O+M**
Required Provisions			
Kitchen	●	○	○
Moisture Prevention + Control	◍◍○○○○○○	○○○○○○○○	○○○○○○○○
Solid Waste	○○	○○	○○
Pest Management	●●◒○○	●●◒○○	◡◡◡○○
Optional Provisions			
Moisture Prevention + Control	●◍◍○	○○○○	○○○○
Solid Waste	○	○	○

Key: Health provision requirements are ...

● ◍ ○ met by required, optional, or not met by GCP measure

◒ ◡ partly met by required, or optional, GCP measure

Noticeably, WELL and NHHS often differ in the range and content of their provisions of biological contaminant provisions (e.g. NHHS includes a total of 2 required solid waste provisions, while WELL has none; Pest Control/Management has 5 required provisions in NHHS, but only 2 optional provisions in WELL). This difference between the two HR Standards may be a factor of their particular foci and target market: NHHS only addresses multifamily residential renovation, while WELL primarily targets new construction. In addition, given the cost of certification itself, NHHS may be utilized more by affordable housing providers than WELL would be.

Overall, the analysis shows that the green certification programs differentially address biological contaminants. Notably, when LEED D+C measures correspond to the Health provisions, they do so as required LEED measures; but when it is LEED O+C, it is as optional measures. Further, neither green program addresses the general need for designing homes that facilitate easy cleaning to the extent that WELL, and to a lesser degree NHHS, prescribe. For example, LEED presents an optional credit for either permanent walk-off mats or a shoe removal and storage area near the main entrance. EGCC does not address either. Relatively simple design solutions such as antimicrobial surfaces and the choice of materials which are easy to clean would require minimal effort to incorporate in these green certification programs.

Chemical Contaminants in IAQ

Gases and particles from fuel-burning combustion appliances, tobacco products, VOCs released from building materials and furnishings, deteriorated asbestos- or lead-containing building materials, household cleaning and maintenance products, and outdoor sources brought indoors, such as pesticides, radon and outdoor air pollution are among the major sources of chemical pollutants indoors (EPA, 2017). Indoor air pollution from chemical contaminants has short-term health effects, such as irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue, and long-term health outcomes, such as asthma, allergies, other respiratory conditions, cardiovascular diseases, and cancer (USEPA, 2017; WHO, 2015). Among the health provisions addressing chemical contaminants, NHHS had 24 required and 8 optional provisions, while WELL had 24 required provisions and 6 optional.

Table 5 shows the correspondence between WELL and the two green building programs. WELL addresses a broad range of aspects affecting indoor air quality for chemical and radiological toxins and details exposure limits on volatile substances, particulate matter and inorganic gases, with post-occupancy air quality testing requirements. Additionally, several WELL required provisions address chemical and particle pollution reduction by limiting VOC emissions from building materials, providing asbestos and lead restrictions, requiring construction pollution management and integrated pest management (IPM) strategies, permanent entryway systems and use reduced-risk pesticide, and imposing indoor and outdoor smoking regulations. Optional provisions include combustion minimization, and reduction of toxic materials such as flame retardants, phthalates, and formaldehyde.

Table 5. Correspondence between WELL and Green Certificate Programs on Chemical Contaminant Provisions

Chemical Contaminants

Health Provisions	Green Certification Program		
WELL	**EGCC 2015**	**LEED v4 HD+C**	**LEED v4 O+M**
Required Provisions			
Air Quality Standards	⯊⯊	◍○*	◍○
Smoking Policies	◡◡	⯊⯊	⯊⯊
VOC Reduction	●●◡◡○*	◡◡◡◡○*	◍◍◍◡○
Air Filtration	○○○	○⯊○	◍◡○
Construction Pollution Mgt.	○○○○○	○○○◍○	○⯊○○○
Healthy Entrance	○○	◡○	◍○
Pesticide Management	○	◡*	◡*
Fundamental Material Safety	●○○○	○○○○	○○○○
Optional Provisions			
Air Flush	○	◍	○
AQ Monitoring + Feedback	○○	◡○	◍○
Advanced Air Purification	○○	○○	○○
Combustion Minimization	●⯊○	⯊⯊○	◍○○
Toxic Material Reduction	⯊○○○○	◡○***	○○○○○
Enhanced Material Safety	○	◍	◍
Cleaning Equipment	○○	◡○	⯊○

Key: Health provision requirements are ...

● ◍ ○ met by required, optional, or not met by GCP measure

⯊ ◡ partly met by required, or optional, GCP measure

* Potential conflict with health measure

However, as illustrated in Table 5, the majority of these standards are not fully addressed in EGCC, LEED HD+M and LEED O+M. As an example, while EGCC has stricter requirements pertaining to VOCs with no or low VOC materials and asthmagen-free materials measures, neither EGCC nor LEED has requirements for air quality testing after occupancy. In addition, LEED HD+C even has certain measures for resource and energy efficiency purposes that may potentially conflict with IAQ. This includes LEED points for using reclaimed, post- and pre-consumer recycled products with no requirement for testing toxic emissions from such products.

Table 6 shows the correspondence between NHHS and the two green building programs. NHHS's required provisions for the most part focus on air sealing between garages and conditioned spaces to minimize air movement that would carry particulates from vehicles. In addition, there are requirements that resonate with lead and asbestos-related standards of WELL. However, NHHS's provisions regarding pesticides, smoking bans, and toxic building materials are not as restrictive as WELL. As NHHS primarily focuses on renovation projects, its health provisions address lead, radon, asbestos, and methamphetamine testing and mitigation. Except for the lead risk minimization with required measures in EGCC and optional measures in LEED, both

GCPs fall short in addressing the testing and abatement of these chemical and radiological pollutants referred to in NHHS.

Table 6. Correspondence between NHHS and Green Certificate Programs on Chemical Contaminant Provisions

Chemical Contaminants

Health Provisions	Green Certification Program		
NHHS	EGCC 2015	LEED v4 HD+C	LEED v4 O+M
Required Provisions			
Heating Systems	◒○○	◒○○	○○○
Air Sealing	○○	●◒	◒○
Chem. + Radiological Agents	◡	◡	○
Lead-Based Paint	●●●●○	◍◍◍◍◍	◍◍◍◍◍
Asbestos	○○○○	○○○○	○○○○
Toxic Substances in Materials	●◒	◍○	○○
Radon	●	○	○
Pesticides	◡○	◡○	◍○
Methamphetamine	○	○	○
Smoking Policies	◍◍○○	●●○○	●●○○
Optional Provisions			
Floors and Floor Coverings	◒○	◍◡	○○
Heating Systems	○	●	○
Air Sealing	○○	◡○	○○
Lead-Based Paint	○	○	○
Radon	○	○	○
Smoking Policies	○○	○○	○○

Key: Health provision requirements are ...

● ◍ ○ met by required, optional, or not met by GCP measure

◒ ◡ partly met by required, or optional, GCP measure

Overall, neither GCP fully addresses the health measures pertaining to indoor chemical pollutants. While EGC seems to have measures that are more comprehensive pertaining to minimizing VOC exposures, our analysis underscored the need for designers and builders to be more proactive about minimizing occupant exposure to chemical contaminants, rather than relying on a single GCP.

Ventilation

Many illnesses, such as those caused by Sick Building Syndrome, can often be traced to inadequate ventilation systems or low air flow rates (Kreiss, 1990). Inadequate ventilation and poorly maintained HVAC systems can contribute to fatigue, nausea, headaches and concentration difficulties (USEPA, 1991) while long-term exposure to poorly ventilated spaces can manifest years later as respiratory conditions, cardiovascular diseases, and cancer (WHO, 2010), immediate effects of poor ventilation can lead directly to death from toxins such as carbon monoxide poisoning (HSE, 2014; Sircar et al., 2015).

WELL contains 3 required and 12 optional provisions addressing ventilation (Table 7) with several unique provisions that are not addressed by the NHHS or the GCPs reviewed. All the reviewed standards address the quality of ventilation to some degree, commonly referencing ASHRAE 62.2 (2010 or 2013) standard as a minimum threshold. After this common reference, WELL sets provisions that are either partially addressed or more commonly left unaddressed by the GCPs including; operable windows, direct source ventilation, and displacement ventilation. This last WELL provision sets four requirements for displacement ventilation (DV), singling out a preferred mechanical system that affects air velocity and helps move pollutants away from occupants through air stratification within occupied spaces.

Table 7. Correspondence between WELL and Green Certificate Programs on Ventilation Provisions

Ventilation

Health Provisions	Green Certification Program		
WELL	EGCC 2015	LEED v4 HD+C	LEED v4 O+M
Required Provisions			
Ventilation Effectiveness	◒◒	◒◒	◒◒
Operable Windows	◡	○	◒
Optional Provisions			
Increased Ventilation	◡	◡	○
Direct Source Ventilation	○○○	○○○	○○○
AQ Monitoring & Feedback	○○○○	○○○○	◡○○○
Displacement Ventilation (DV)	○○	○○	○○
DV System Performance	○○	○○	○○

Key: Health provision requirements are ...

● ◍ ○ met by required, optional, or not met by GCP measure

◒ ◡ partly met by required, or optional, GCP measure

What might be somewhat more unusual than WELL's advocacy for DV systems is the GCPs minimal incorporation of provisions discussing operable windows. WELL requires all regularly occupied spaces to have operable windows and addresses concerns for maintaining indoor air quality. In contrast, EGCC does mention operable windows in the Passive Solar Heating Strategies section, and LEED O+M references requirements for operable windows in every bedroom within a multifamily building; yet neither addresses the feature as extensively as WELL's provision. This may be due in part to the ubiquitous presence of operable windows in the typical home and a reasonable assumption that any new or existing home would most likely have operable windows due to local building code requirements and common home design and building practices. However, this lack of attention to such a common architectural feature neglects to offer health and energy benefits that operable windows bring to a space, including improved air quality, natural ventilation, daylight, and reduce energy use.

NHHS includes 5 required and 1 optional provision regarding ventilation (Table 8). These provisions tend to be more easily incorporated into common home building practices, focusing on issues of well-designed HVAC systems (referencing ASHRAE 62.1 and 62.2 standards), adequate ventilation for humid rooms (bath and laundry rooms), and appropriate locations for the air handling intake. The GCPs tend to be more successful in reflecting NHHS provisions as they are generally limited to design features that can be more easily accommodated with existing building practices than meeting the more ambitious WELL provisions.

Table 8. Correspondence between NHHS and Green Certificate Programs on Ventilation Provisions

Ventilation

Health Provisions	Green Certification Program		
NHHS	EGCC 2015	LEED v4 HD+C	LEED v4 O+M
Required Provisions			
HVAC Systems	○	◒	◒
Ventilation	●◒○○	●●○○	○○○○
Optional Provisions			
Ventilation	◒	○	○

Key: Health provision requirements are ...
● ● ○ met by required, optional, or not met by GCP measure
◒ ◒ partly met by required, or optional, GCP measure

CONCLUSIONS

This analysis illustrates that green building addresses certain health-related occupancy concerns, but it is far from being comprehensive. In a few instances, there are even possible conflicts between GCPs and HR standards that may actually exacerbate or compromise occupant health. Such findings illustrate the need for those architects and builders who wish to prioritize *both* green design and health in housing projects to refer to multiple certification systems.

Design and construction guidance for addressing occupant health is improving with the development of HR standards like WELL and NHHS. However, these standards are not all-encompassing solutions for every health-related issue, and they are likely to continually evolve as the green certification programs do. For example, two health-related issues — Active Design that comprises design strategies to promote physical activity (Center for Active Design, 2017), and Inclusive (Universal) Design that aims to enhance mobility and accessibility in the home for occupants with diverse capabilities and needs (The Center for Universal Design, 2008) — are addressed to a greater extent in the green certification programs than in these two HR Standards. The ongoing collaboration efforts between the International WELL Building Institute and Green Building Certification Institute (GBCI) may be interpreted as how developers of GCP and HR programs recognize the need to collaborate to better synchronize green building with health and wellness certifications, and be able to incorporate the currently missing health issues in future versions of these programs (Long, 2015; USGBC, 2014)

Finally, a critical point to note is that several health provisions are addressed by LEED's Operations and Maintenance (O+M) certification, but are not included in the design and construction certification program. Originally, the analysis was limited to reviewing only green design guidelines typically used by architects and builders during the new construction phase and not the O+M certification. However, from the analysis it is evident that many health related issues could be simplified for the ongoing maintenance and operation of a home if designers make a conscious effort to consider these issues when design spaces and material selection. With initial design decisions having long-lasting effects on both occupant health and wellbeing, and in reducing challenges associated with maintaining a healthy home, utilizing an integrated design process becomes increasingly important for incorporating the crucial role of facility management in maintaining multi-family housing as both energy efficient and healthy for their residents.

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Compartmentalization as a solution to managing stack effect in tall residential buildings

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Abstract

Air movement can have a major effect on the energy performance and serviceability of tall residential buildings. Airflow occurs vertically, through elevator shafts and stairwells, or laterally through doorways, operable windows, and leakage openings in the building envelope. Air movement is caused by pressure differences created by a combination of stack effect, wind effect, mechanical ventilation, and elevator piston effect. However, during the heating season, stack effect is a major contributor to air movement in tall residential buildings in cold climates.

The first objective of this paper is to review stack effect related issues in tall residential buildings. Three problems are summarized from issues commonly reported, which are life safety, serviceability, and ventilation related issues.

Several mitigation strategies including active and passive strategies are discussed in this paper, as well as their limitations when applied to tall residential buildings. This paper then identifies 'compartmentalization' as a reliable approach to mitigating stack effect induced problems. Compartmentalization is an effective solution for controlling airflows in tall residential buildings, especially air flows related to occupants opening windows or balcony doors.

Assessing the extent to which tall residential buildings are currently being compartmentalized is difficult because field measurement data are generally, unavailable. Hence, the third goal of this paper is to investigate ways in which airtightness data can be gathered in order to evaluate the effectiveness of compartmentalization. This paper examines three common challenges when conducting airtightness test in tall residential buildings, which are inconsistency in testing method, airtightness metric and documented normalized surface area.

1 Stack Effect

Stack effect, refers to the movement of air in a building and through openings in a building's envelope due to temperature difference between the inside and the outside of the building; the taller the building, the greater the effect (Hutcheon & Handegord, 1994; Tamura & Wilson, 1968). As shown in Figure 1, the air movement occurs when we tend to condition indoor air by heating it in winter and cooling it in summer. Cold air is more dense than warm air, resulting in a difference in pressure across the building envelope.

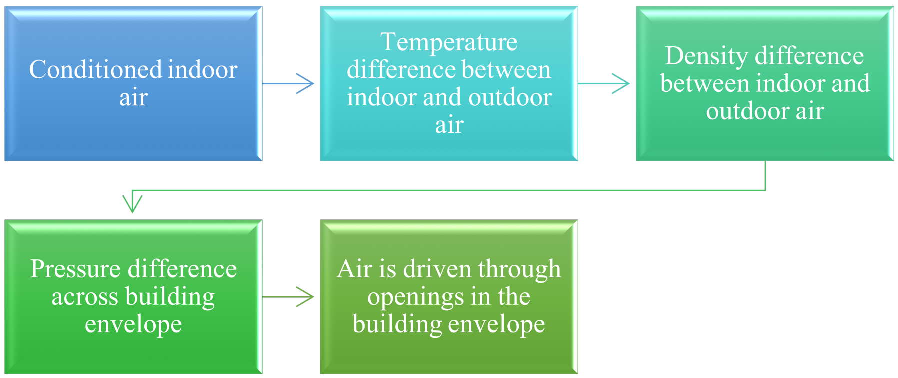

Figure 1. Diagram to Illustrate Stack Effect Drivers

During the heating season, under calm wind conditions with no fans operating, the dense cold outdoor air is at a higher pressure than the warm indoor air at the same level. The difference is greatest at the ground level, driving cold air into the building (infiltration). The warm conditioned air is driven toward the upper levels, where it attempts to exfiltrate. Somewhere between the ground and the top floor, the inside and outside air pressures are equal; this is called the neutral pressure plane. Similar airflows take place in conditioned shafts and stairwells within a building. A reversal of this airflow occurs during the summer when the air inside the building is being cooled below the temperature of the outside air. This is known as "reverse stack effect."

1.1 Problems Related to Stack Effect

Stack effect induced problems in tall residential buildings are numerous and have been extensively investigated and reported (Hill, 2006; Jo, Lim, Song, Yeo, & Kim, 2007; Song, Lim, Lee, & Seo, 2014). This paper summarizes those problems into three categories, namely life safety, serviceability, and ventilation related issues.

The most severe safety hazard is a fire event. Driven by pressure differentials, the rising smoke and other air-borne contaminants account for most of the fatalities in a fire event. The 26-story MGM Grand Casino Hotel in the 1980's is a well-documented example (Best & Demers, 1982). The fire broke out on the ground floor of the hotel, then the smoke migrated vertically throughout the building. Sixty-one of the 85 fatalities occurred above the 16th floor were due to smoke inhalation (Klote, 2015). In less catastrophic situations, stack pressures can drive cooking odors, tobacco smoke, and other air-borne contaminants between suites, hereby significantly affecting the indoor air quality in multiunit residential buildings (MURBs).

The second category is building serviceability. A high pressure differential can cause difficulties in operating swing doors and elevator doors, especially for those located at the ground or top floors (Tamblyn, 1991). To maintain smooth operation, studies have suggested that the maximum pressure difference across a single swing door should be 50 Pa, and 25 Pa for elevator landing doors (Lovatt & Wilson, 1994; Tamblyn, 1993). Other serviceability issues include whistling noises and uncomfortable air flow volumes that can adversely affect occupant comfort. From a field study involving a 40- and a 69-story residential building in Korea, the measured pressure differentials across swing doors and elevators were found to exceed the suggested pressure difference limits and the unpleasant whistling sounds were found to be as loud as 60 - 70 dB (Jo et al., 2007; Koo, Jo, Seo, Yeo, & Kim, 2004).

The third category is the ventilation system efficiency. Corridor ventilation systems, commonly used in residential buildings in Canada, use fresh outdoor air to pressurize the common corridors and drive ventilation air into units. To provide sufficient ventilate air to the suites, the ventilation system requires great amount of outdoor air to combat the pressure differences induce by stack effect. One study of mid- and high-rise residential buildings in British Columbia found by simulation that an average of 19% of the annual energy was used for ventilation heating (Finch, Burnett, & Knowles, 2009). In Canada's colder regions, a simulation study found that up to 25% of space heating energy use was associated with the ventilation system (CMHC, 2017). More details regarding the corridor ventilation system can be found in Section 2.1.1.

1.2 Stack Effect in Tall Buildings vs Low-rise Buildings

The magnitude of stack effect is proportional to the indoor/outdoor air density difference and the building height. For two buildings in the same general location, the taller building would experience a stronger stack effect. For low- to mid-rise buildings, stack pressure differences are relatively small. Hence, the air movement within the building is dominated by either wind-induced pressure differences or pressure differences induced by mechanical ventilation. Therefore, problems associated with stack effect and air leakage are exacerbated in tall buildings, which can have serious impacts on building performance.

A graphical illustration of the stack pressure variation versus height above the neutral pressure plane is shown in Figure 2 for various temperature differences (Hutcheon & Handegord, 1994). For a 30-story building, assuming the neutral pressure plane is located at mid-height, a stack pressure difference around 60 Pa will develop when the outdoor air temperature is -10^{o}C and the indoor air temperature is 20^{o}C.

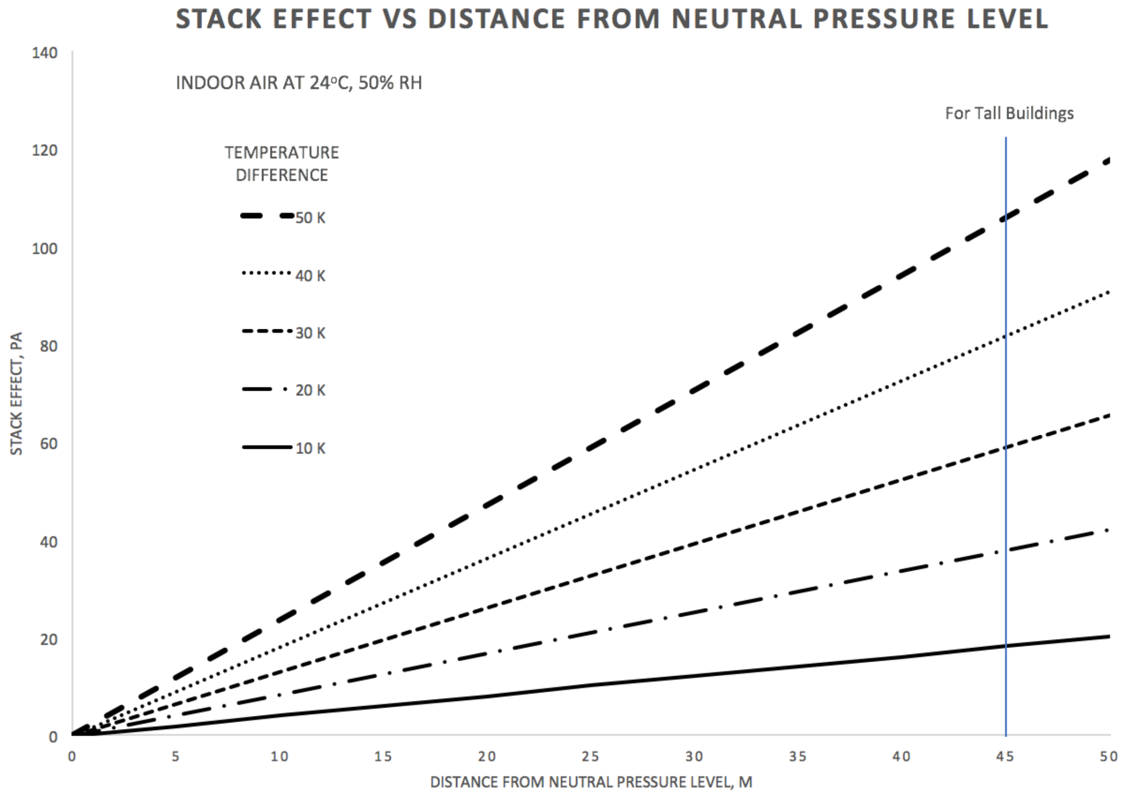

Figure 2. Theoretical Pressure Differential due to Stack Effect Applied on Buildings (Adapted from Hutcheon & Handegord, 1994)

The definition of a tall buildings varies by source, and can be based on the building height or the number of floors. The concept of a tall building is subjective depending on its surrounding environment, the height to width ratio of the building, and the implementation of tall building related technologies (CTBUH, 2017). A more quantitative definition is a building taller than 91m (ASHRAE, n.d.). As such, a tall building in this paper is defined as a building taller than 90 m or approximately 30 stories, which is shown at the far right of Figure 2.

1.3 Stack Effect in Residential Buildings vs Commercial Buildings

In addition to building height, the impact of stack induced problems varies by building types. For instance, problems associated with stack effect can be more serious and difficult to control in residential buildings than in commercial offices. Commercial buildings often lack operable windows. If constructed airtight, the wall provides a reliable barrier to air movement across the building envelope - if exfiltration is prevented, then so is infiltration at ground level. Residential buildings, on the other hand, typically have operable windows and balcony doors - important features to residential occupants. These openings compromise the building's airtightness and enhance air leakage due to the stack effect when doors and windows are opened or incompletely closed. Occupant behavior is therefore a critical factor, making residential buildings particularly problematic in the control of air movement.

Another difference between commercial and residential building is the existence of internal partitions which can make operating elevator and stairwell doors a bigger problem for residential buildings. Field measurements at a 44-story office building in Montreal showed that the pressure differences across elevator landing doors at some floors exceeded the operation threshold by as much as 4 times (Lovatt & Wilson, 1994). In the open floor plans of many office buildings, most of the stack pressure differences are concentrated across the exterior enclosure (63% - 82%) (Tamura & Wilson, 1968). In a residential building with the same exterior façade airtightness and building height, the stack pressures from the exterior enclosure are often redistributed across the internal partitions and elevator and stairwell doors, potentially increasing the pressure difference at the operable doors.

1.4 Scope and Objectives

Tall residential buildings in cold climates experience serious stack effect related problems. Factors that contribute include building height, inside-outside temperature difference, building envelope construction details, and, occupant behavior. This paper provides a review of existing literature on the means of mitigating stack effect in tall residential buildings in cold climates. The specific objectives of this research are:

- To review stack effect related issues in tall residential buildings;
- To evaluate active and passive approaches suggested in the literature to mitigate stack effect, and
- To investigate the limitations of current methods for testing the successful implementation of compartmentalization, a promising mitigation strategy.

2 Approaches to Mitigate Stack Induced Problems

Reliable and effective solutions to mitigate issues induced by stack effect is critical especially for tall residential buildings. The literature provides recommendations for mitigating strategies, which are grouped here as active and passive strategies.

2.1 Active Strategies

The active approach used to control the impact of stack effect involves adjusting indoor air pressures using mechanical systems. Some active strategies mentioned in the literature include Mechanical Pressurization System and Mechanical Ventilation in Elevator Shaft Space.

2.1.1 Mechanical Pressurization System

The mechanical pressurization system reduces the influence of stack effect by pressurizing all floors or partially the lobby entrance area to maintain a positive pressure difference on building envelope (Tamblyn, 1993). Outdoor air is taken from an air handling unit on the rooftop and then distributed to the corridor on each floor. Due to a higher pressure, the corridor air is forced to the living unit through suite entrance door undercuts, and eventually pushed to the outside.

But the mechanical pressurization system fails to consider the overall stack pressure distribution in a building. A study conducted on a 13-story MURB suggested the lower and upper portions of the building were significantly under- and over-ventilated respectively (Ricketts & Straube, 2014). The negative stack pressure on the lower portion of the building neutralizes the positive ventilation pressure across the suite envelope. Meanwhile, the exfiltration airflow is a total combination of both outward ventilation and stack-induced flows on upper floors. Moreover, as a ventilation system, it fails to deliver fresh air at the designed rate to the suites. From the same study, researchers found that only 8% of air brought in by the air handling unit made its way through the duct system into the corridor, and into the suites through unit entrance door undercuts. The remaining 92% of conditioned air contributed to the uncontrolled airflows in the building (Ricketts & Straube, 2014). Therefore, this strategy as a solution to stack effect is proven to be undesirable in practice.

2.1.2 Mechanical Ventilation in Elevator Shaft Space

The mechanical ventilation in elevator shaft space approach reduces the stack-induced pressure differences by changing the air temperature inside the elevator shaft. This can be achieved by introducing outdoor air to the shaft through several diffusers, and ventilation openings located on the roof top to keep the shaft space from being pressurized. During the heating season, the air density inside the shaft increases when it is mixed with outdoor cold air. Hence, the pressure difference at the bottom and top of the building can be reduced. In one study, the mechanical ventilation system was installed in a 41-story commercial building. By cooling the average temperature of the shaft by 5 ^{o}C, the velocity of air passing through elevator doors was reduced by 41% at the lobby level and 48% at the top floor when elevator doors were open (Song et al., 2014).

Some secondary problems may occur when lowering the air temperature in elevator shaft, such as condensation on the shaft walls, occupant discomfort, and thermal loss due to heat exchange with the warmer zones in the building. The most concerning issue is the resistance to non-stack driven airflows. Since the elevator hoist is connected to the outside at the top of buildings, the ventilation fan and leaks at the connections can significantly enhance the airflow through the building. Although the stack pressure difference potential is reduced, the system has no resistance to airflow generated by strong winds and the building ventilation system. Therefore, ventilating the elevator shaft is not a favorable solution.

2.2 Passive Strategies

Relative to active strategies, passive mitigation is a more reliable approach to control varying airflows by restricting flow paths. Five passive strategies are discussed next.

2.2.1 Vertical Zoning

In vertical zoning, elevator travel is restricted to designated floors. One common application is the disconnection between the garage and upper residential floors. Passengers in the garage must take the elevator to the lobby floor, then transfer to another elevator to access their suites. It is effective in preventing garage contaminated air from migrating into occupied floors. There are some applications for tall buildings to have three elevator zones for high-, mid- and low-rise floors. Field measurement found that vertical zoning is able to mitigate stack pressures and airflow excepting for the floor where two elevator zones meet each other (Jo et al., 2007).

However, the downside is the inconvenience for residents since they may need to transfer elevators for a single trip. Also, vertical zoning requires several sets of elevator banks, which may result in inefficient floor area planning and use.

2.2.2 Revolving Door and Vestibule

The revolving door and vestibule is a very successful solution to air infiltration or exfiltration due to stack pressures that has been implemented almost in every high-rise residential and commercial tower. The revolving door can be easily operated since the stack pressure exerting on one glazing door is balanced by the pressure on the other panel. The amount of cold air that can rush into the lobby is limited by the volume between two door panels. For vestibules, the stack pressure differences are redistributed between the set of swing doors, hence, it reduces the actual pressure difference cross each door panel to below the operation threshold. A field measurement conducted on 23 buildings concluded that the building main entrance doors can account for nearly 30 to 70% of the air leakage due to stack effect (Hutcheon & Handegord, 1994). Therefore, revolving doors and vestibules are frequently suggested (Jo et al., 2007; Lee, Hwang, Song, & Kim, 2012; Tamura & Wilson, 1968).

The effectiveness of this strategy can be compromised by occupant behavior. For instance, an open window on the second floor can provide an infiltration path and shortcut the air barrier design of building entrance doors. Holding both doors open in the vestibule can also reduce their effectiveness. Moreover, the revolving door and vestibule is limited by the architectural layout of the lobby, which sometimes makes the installation impossible in a retrofitted building.

2.2.3 Improving Exterior Envelope Airtightness

A more holistic passive mitigation strategy is improving the airtightness on the entire building. The building enclosure is often treated as the primary air barrier system because it separates the indoor air from the ambient (Lovatt & Wilson, 1994; Tamura & Wilson, 1968). Having the exterior envelope constructed airtight is essential in reducing air exfiltration. It has achieved successful results in commercial buildings. However, for residential buildings, the benefits of having an airtight envelope are compromised by poorly sealed or open windows and balcony doors (CMHC, 1996).

When windows are open, the indoor pressure of the suite becomes similar to the outdoor pressure. This increases the pressure difference across the demising wall between the suite and its adjacent units. Studies have shown that 12 to 36% of the total airflow into a suite can come from adjacent suites instead of the ambient environment (Levin, 1988; Palmiter, Heller, & Sherman, 1995). A field measurement conducted on six residential buildings in Minnesota found that on average 27% of the air leakage came from adjacent units (Bohac, Fitzgerald, Hewett, & Grimsrud, 2007). However, the range of tested results for an individual unit varied from 1% to 65% depending on the quality and type of construction. There was less leakage at the demising wall if the building was newer, constructed with airtight material (concrete), or if the unit was located on a lower level (Bohac et al., 2007).

A survey of the window opening rate was conducted on a 15 and 17 story MURB in Winnipeg, Canada (Proskiw & Phillips, 2008). For the 17-story building, researchers observed that about 8.8%, 7.0% and 2.3% of suite windows would be opened when the ambient temperature is at 20°C, -4°C and -25°C respectively. Windows in the 15-story building were left open even at temperatures of - 40°C. Moreover, the frequency of leaving a window open was related to its location in the building. During -25°C weather, 1 - 2% of the windows were left open on lower floors, while 5 - 10% were open on the floors above the neutral pressure plane. This demonstrates that the in-situ airtightness of the building envelope is not directly related to the design and workmanship; instead, occupant behavior dramatically affects the airtightness performance.

2.2.4 Improving Interior Partitions Airtightness

Air leakage through interior partitions occurs at the top and bottom of the walls, wall penetrations, floor penetrations at utility stack runs, and around suite doors. Similar to building envelope issues, the effort spent on air barrier materials and assembly sealing details on interior elements can be discounted when the suite-corridor door is opened. With more stack pressure found across the demising walls, the suite entrance, stairwell and elevator doors become more difficult to operate.

2.2.5 Improving both Exterior and Interior Partitions Airtightness

To effectively mitigate stack effect, both exterior and interior air tightness should be improved. This leads to the introduction of compartmentalization, which is discussed next.

3 Compartmentalization

The goal of compartmentalization is to separate each zone from its surrounding space in multi-zone buildings. Instead of looking at the building as a whole, vertical shafts, corridors, and suite units are isolated and disconnected when the doorways are closed. Isolation can be achieved by installing a continuous air barrier system along the perimeter of each zone. However, during construction, careful attention must be directed toward connections and pipe penetrations at the boundaries of the zones. Compartmentalization can achieve a variety of goals by limiting the vertical and horizontal air movement across building spaces (CMHC, 2005; Finch, Straube, & Genge, 2009; RDH, 2013). These include:

- Increasing occupant comfort by providing a better control of indoor air temperature and relative humidity;
- Reducing the energy consumption of space conditioning (heating and cooling);
- Improving smoke migration control in a fire event;
- Preventing migration of odors, tobacco, and cooking smoke from adjacent units; and,
- Enhancing reliable ventilation in the suite space and downsize the ventilation equipment for the common area.

The greatest advantage of compartmentalization is moderating the effect of occupant behavior. By creating multiple interior partitions, compartmentalization effectively reduces the possibility of a resistant-free airflow path across the building. For instance, when a suite window is open, partition walls around the suite would function as a secondary air barrier system, preventing airflow into adjacent spaces. The concept of compartmentalization specifically targets residential buildings.

3.1 Approaches to Implement Compartmentalization

There are three approaches to executing the compartmentalization strategy (CMHC, 1996). The first one is referred to as "unit compartmentalization." By addressing the airtightness of enclosures on all six sides, the suite is isolated from the adjacent living units, corridors, and the ambient environment. For the rest of the building, vertical shafts remain connected to the corridor on each level.

The second method is the "floor-by-floor compartmentalization." The objective of this approach is to reduce stack effect by preventing the vertical flow of air. It is achieved by ensuring airtightness between the corridors on each floor and the vertical shaft, such as elevators, stairwells, and utility runs, leaving the corridor and suites connected. Unfortunately, it is difficult to make the elevator landing door airtight, due to limits on their maximum closing power. This method is commonly adopted in commercial buildings, with the implementation of elevator lobby vestibules on every floor.

One potential problem associated with the first two methods is the pressure differential accumulated at the airtightness partition layer. The high-pressure differential would exceed the pressure thresholds, resulting in difficulty operating doors and potential constant whistling noise around doors (CMHC, 1996).

Finally, "double compartmentalization" is a hybrid strategy that emphases airtightness on both the suite and floor level. In this way, stack pressures can be redistributed throughout multiple internal partitions and the exterior envelope, so that the problems related to accumulated pressure can be mitigated. However, double compartmentalization increases the amount of time and cost required to ensure properly sealed interiors.

In 1996, a 12-story residential building in Nepean, Ontario was used to test different compartmentalization strategies (CMHC, 1996). The stack pressures and airflows in the existing building were measured, and a computer modeling software named CONTAM was used to simulate results from the three approaches. In the model, each compartmentalization strategy was simulated by replacing the suite or elevator landing doors with the most airtight doors, available at that time. It was estimated that the total airflow entering the building could be reduced by 12%, 4%, and 14% respectively using unit, floor-by-floor and double compartmentalization strategies. Even though the double compartmentalization achieved the best performance at 14%, unit compartmentalization (12%) was more cost-effective and recommended by the study. The modelling results also demonstrated that compartmentalization could be used to control the effect of opening windows and doors. In the model, one door (e.g. suite or elevator landing door) on the top floor was set to "open", and the pressure differential and airflow rate was calculated for a unit on the middle floor and ground floor. For all three types of compartmentalization, the pressure exerting on the suite door at the 1st and 6th level remained the same as the "all doors closed" scenario. Therefore, the compartmentalization strategy is indeed effective in reducing stack induced pressure differences and airflows while accounting for occupant behavior.

However, the unit compartmentalization strategy is not always preferred, especially in very tall towers. For high-rise and tall residential buildings, the pressure differential across suite entrance doors from unit compartmentalization can greatly exceed the allowable operation threshold of 50 Pa. Hence, there is a practical limitation for improving the airtightness of unit enclosures, so that a double compartmentalization strategy is required for tall residential buildings.

4 Assessment of Compartmentalization in Tall Residential Buildings

Air leakage rates can be used to quantify the airtightness of an interior partition or exterior enclosure. It can also act as an indicator of the level of compartmentalization that a building has achieved. Hence, airtightness values for existing MURBs, if they were available, could be very helpful in assessing the effectiveness of compartmentalization strategy in existing tall residential buildings.

Table 1 summarizes previous studies of MURB's leakage assessment. Because the results were expressed in different metrics, all airtightness values are converted into Normalized Flow Index as $L/s/m^2$ at 75 Pa for comparison purpose.

Table 1. List of previous field measurements on airtightness of existing MURBs

Previous Study		(Gulay, Stewart, & Foley, 1993)	(CMHC, 2005)	(Hill, 2006)	(Finch, Straube, et al., 2009)	(Klocke, Faakye, & Puttagunta, 2014)
Number of Buildings		11	3	1	4	3
Building Location		Canada	Canada	Canada	Canada	USA
		Various Location	Ontario	-	British Colombia	New York
Building Construction Time		1960-1991	Near 2005	-	1980s-2000s	2013
Building Height [Story]		6-13	16-29	29	4-26	2-3
Testing Method		Whole Building Test & Guarded Blower Door Test	Suite/Floor Blower Door Test	Suite/Floor Blower Door Test	Guarded Blower Door Test	Suite/Floor Blower Door Test
Airtightness of Interior Partition [L/s/m2 at 75 Pa]	Min	-	-	-	0.27	-
	Max	-	-	-	2.07	-
	Mean	-	-	-	0.98	-
Airtightness of Exterior Envelope [L/s/m2 at 75 Pa]	Min	0.89	-	-	3.3	-
	Max	14.2	-	-	16.04	-
	Mean	-	-	-	7.34	-
	Min	-	0.35	0.38	0.77	0.53

Airtightness of Suite Enclosure [L/s/m2 at 75 Pa]	Max	-	1.01	1.23	3.77	1.98
	Mean	-	0.75	0.61	1.81	1.35
Note		A	B	C	D	E

Previous Study		(Ueno & Lstiburek, 2015)	(CMHC, 2001)	(RDH, 2013)	(RDH, 2015)	(Jones, Brown, Thompson, & Finch, 2014)
Number of Buildings		1	23	43	113	11
Building Location		USA	Canada	Canada, USA	Canada, USA, UK	USA
		Washington D.C.	Various Location	Various Location	Various Location	Washington
Building Construction Time		-	1965-2001	1956-2011	1910-2014	After 2010
Building Height [Story]		3	1-21	1-23	1-25	1-5
Testing Method		Suite/Floor Blower Door Test & Guarded Blower Door Test	Whole Building Test & Guarded Blower Door Test	Whole Building Test & Guarded Blower Door Test	Whole Building Test	Whole Building Test
Airtightness of Interior Partition [L/s/m2 at 75 Pa]	Min	-	-	0.41	-	-
	Max	-	-	7.98	-	-
	Mean	-	-	3.10	-	-
Airtightness of Exterior Envelope [L/s/m2 at 75 Pa]	Min	1.32	0.83	0.81	0.35	0.71
	Max	1.65	10.00	10.01	19.22	2.54
	Mean	1.48	3.68	3.96	3.09	1.55
Airtightness of Suite Enclosure [L/s/m2 at 75 Pa]	Min	1.45	-	0.71	-	-
	Max	2.05	-	3.3	-	-
	Mean	1.8	-	1.73	-	-
Note		F	G	H	I	J

Note:

A. *Airtightness value converted from Normalized Flow Index at 50 Pa*
B. *The whole building test was conducted on the suite level*
C. *The whole building test was conducted on the suite level*
D. *Airtightness value converted from ELA50 and ACH50*
E. *The whole building test was conducted on the suite level; Airtightness value converted from Normalized Flow Index at 50 Pa and ACH50*
F. *Leakage flow occurred during guarded blower door test, because the cavity within suite adiabatic wall was connected to the ambient*
G. *The whole building test was conducted on the suite, floor and building level*
H. *There are 6 suites tested under guarded blower door test. The significant low overall suite leakage is likely due to the design intention for LEED requirements*
I. *Comparing with the previous literature review by the same author, there is only one 25-story MURB added into the database for buildings above 20 floors*
J. *There is no further declaration on building height, completion time and other details. The building information is assumed in accordance with the SEC 2009 building code*

A review of over 100 publications related to airtightness around the world (Sherman & Chan, 2006) showed that most of the field measurement studies in North America were performed on low-rise (Lagus & King, 1986; Reardon, 1987; Love, 1990) to mid-rise (Shaw et al. 1991, Palmiter et al. 1995, Nichols & Gerbasi 1997, and Zuercher & Feustel 1983) residential buildings. Unfortunately, these works did not focus on stack effect as it is not significant at these limited building heights.

No airtightness data for buildings over 30 stories were found. In the 25-30 story range, the available tested results are limited to four high-rise residential buildings.

Ten units in two 29-story residential buildings were tested using a single blower fan to depressurize the suite space, hereby the airtightness of the suite enclosure were tested (CMHC, 2005; Hill, 2006). Although the building information is not clearly documented in Hill 2006, the context suggests that the two tested buildings are the same. In a 26-story residential building (Finch, Straube, et al., 2009), guarded blower door tests were conducted for one unit, which provided separate airtightness results of the suite enclosure, exterior envelope and internal partitions. As not floor-to-ceiling height was provided, it was assumed to be 2.44m when converting the airtightness unit in Table 1. The airtightness rate of a 25-story building exterior envelope was estimated to be around 0.8 $L/s/m^2$ at 75 Pa, resulted from using the whole building test (RDH, 2015).

It is difficult to compare the airtightness results from these few buildings that given the diversity in testing methods and objectives. Therefore, these three measured sample points are insufficient to draw statistically significant conclusions on the general airtightness characteristics of tall residential buildings. The next section looks at the detail of the common contributors making airtightness measurement in tall residential buildings challenging.

5 Limitations in Measuring Airtightness in Tall Residential Buildings

The compartmentalization strategy has great potential to be an effective and reliable solution for tall residential buildings. However, there is no evidence that compartmentalization has been successfully implemented in tall residential buildings. To understand why the data are not available, three difficulties in applying the current airtightness assessment process to tall residential buildings are analyzed; namely inconsistency in testing method, airtightness metrics, and normalized surface area calculations.

5.1 Inconsistency in Testing Methods

There are two commonly adopted testing methods for testing airtightness in North America: whole building tests and guarded blower door tests. Each testing scheme has unique advantages, as well as practical limitations. Hence there is no universal agreement on airtightness testing procedures for multiunit residential buildings.

5.1.1 Whole Building Test

The whole building test was first developed to gather information about air leakage in single detached houses. By depressurizing the entire house using a blower door fan, the airflow across the building envelope can be calculated and the overall leakage rate determined. Eventually, fan depressurization was widely adopted in North America as a means to evaluate the airtightness of single-family detached homes. However, the whole building test has practical limits when testing large volume spaces, and cannot be readily used to evaluate the airtightness of large buildings.

The first limiting factor is the building volume (RDH, 2015; Sherman & Chan, 2006; Urquhart, Richman, & Finch, 2015). For buildings with large floor areas, the conventional blower fan used for testing houses is not capable of providing sufficient flow to maintain a high pressure difference. For instance, to test a building over 1000 m^2, either multiple blower doors need to operated simultaneously, or a single high capacity fan can be installed to depressurize or pressurize the building (John Straube, 2014). The accuracy of the field test data can be compromised when multiple blowers operate simultaneously (CMHC, 2001). Conversely, operating the high capacity fan is extremely difficult from a logistical perspective, due to the lack of equipment, mobility issues, and additional power requirements.

The second limiting factor is the testing conditions. Prior to the test, all of the intentional openings such as HVAC intakes and exhaust grills, kitchens and bathroom exhaust ducts, and relief dampers must be prepared (John Straube, 2014). Three types of preparation can be done to those openings: sealed, closed, and untouched. In one field study, the measured leakage results extrapolated from depressurization and pressurization tests were contradictory because the passive exhaust fan was left intact (Urquhart et al., 2015). Errors can easily be introduced when testing residential buildings if the preparation procedure is not well defined and implemented.

The third limiting factor relates to the control of windows and doorways. A study on whole building tests conducted on six occupied MURBs with 1 to 13 stories, summarized major difficulties related to field measurements (Red River College, 2015).

a) Suite Entrance Door

The whole building test requires a uniform pressure change in the entire tested space. Having the interior suite door closed could result in a pressure difference between a suite and the adjacent corridor being greater than 75 Pa, although the error in measured leakage was within a tolerable range (3% - 5%). As the experiments were performed on two small buildings (one-story and six-story), one might expect that the impact of not having all the interior spaces connected will be much more severe as the building scale increases.

b) Suite Window

Window openings can greatly affect air leakage results. The field test found that results could not be used even if one single window was open. Although windows were closed prior to the test, many were found open either due to occupant interference or the force generated during the pressurization test. A crew was assigned to observe window conditions from the outside, and the test was paused several times to fix window issues. For tall residential buildings, it may be impractical to continuously monitor the position of each window.

c) Building Entrance Door

Similar to open windows, building entrance doors can also significantly affect the test results. Access control must be implemented to ensure test consistency. It requires the full cooperation of the property management team and the tenants for occupied buildings, or a well-planned schedule with subcontractors and suppliers for buildings under construction.

Lastly, the whole building test is only able to determine the airtightness of the exterior envelope of the building. It cannot provide information on interior party walls, which makes it unsuitable for investigating compartmentalization. The practical limits of conducting whole building tests make it extremely difficult and potentially unreliable for large buildings.

5.1.2 Guarded Blower Door Test

To solve problems arising from larger scale buildings and complex connected floor plans, a method called guarded blower door test was developed to examine individual suites. This method isolates the test space by creating a 'guard' or neutral pressures zones that completely surround the suite in question so that air leakage can be isolated to the building assembly of interest (Reardon & Shaw, 1988; Shaw, 1980). The guarded blower door test prevents leakages across interior partitions by maintaining the same pressure on each side of a partition, hereby eliminating the pressure differences across the partitions. This requires installing, running, and coordinating multiple fans in the spaces adjacent to the tested suite.

In contrast to the whole building test, the guarded blower door test can provide airtightness information on both exterior and interior partitions. One advantage for high-rise residential buildings, is that the test is conducted at the suite level, rather than the full building. Many limitations identified in the whole building test can be mitigated using this testing method.

However, the guarded blower door test is not widely used by practitioners in the building industry. The major practical difficulty is coordinating multiple running fans to eliminate the pressure difference across any internal partitions. For example, the pressure in the corridor is susceptible to the piston effect resulting from elevator motion. The opening of the elevator landing doors has great impact on corridor pressures as well. The complex internal geometry in residential buildings increases the difficulty of maintaining a steady pressure, which compromises the measurement accuracy (CMHC, 2001; Urquhart et al., 2015). To combat the variables in field measurement, experienced personnel are required to perform the test, and strict protocols are needed to adjust for repeating experimental processes and to account for non-uniform testing conditions.

Although the guarded blower door test is intended to eliminate the internal flow, the measured flow result may still include leakages through partitions due to demising wall construction. In one case (Ueno & Lstiburek, 2015), the wall cavities between adjacent units were unknowingly connected to the ambient environment. During the test, air leaked out from the pressurized unit and flowed to the outdoors through the wall cavity even though the pressure difference was balanced at the demising wall. It has been concluded that the guarded blower door test is too costly and time intensive to be applied as a common airtightness testing method (Finch, Straube, et al., 2009).

5.1.3 Suite/Floor Level Blower Door Test

Suite/Floor level blower door test is an adaptation of the whole building test. Instead of conducting the test on the entire building, only one blower fan is required to be installed to de- or pressurize the individual suite or floor space. This testing method measures the overall airtightness of the suite or floor enclosure, including exterior walls, internal partitions, floor and ceiling slabs. This testing method is a promising means of measuring airtightness of compartmentalized residential buildings, since it requires cheaper equipment, less time for test preparation, simpler coordination and less access of the tested space.

However, there is no standardized guidelines for conducting the suite/floor level blower door test. Previous field measurements used protocols for the whole building test as the general guidelines when conducting this alternative test. But errors can be introduced when interpolating and applying the guidelines differently. In the case of the 29-story building mentioned in Section 4, both studies conducted suite level blower door test following the CAN/CGSB 149.10 protocol that specifically developed for testing detached house using whole building test (CMHC, 2005; Hill, 2006). However, the fan was installed at the balcony door or window openings in one study, while the blower was located at the suite entrance door in the other project. The leakage that occurs where the fan is installed was not explicitly reflected in the measurement, hereby it creates difference in test results, even when testing on the same suite.

5.2 Inconsistency in Airtightness Metrics

A proper metric is essential to reflect the in-situ airtightness for the air barrier system, and enables tested results to be compared. The selection of unit depends on and varies by the testing method. In this section, airtightness metrics are introduced. Finally, an appropriate unit for tall residential buildings is recommended.

5.2.1 Air Change Rate

A common metric is air changes per hour at 50 Pa (ACH50). ACH50 represents the number of times that the air inside a space is replaced per hour when the pressure differential across the enclosure surface is 50 Pa. The metric is calculated by dividing the total air leakage flow in one hour by the space volume.

ACH50 is a good indicator when the tested target has a relatively large floor area such as detached houses. But results expressed in ACH50 for relatively small volume-to-surface ratio spaces can be misleading and seem much leakier than they are. Consider two suites from one residential building - the airtightness rate of each suite should be reasonably similar, say, 2 $L/s/m^2$ at 75 Pa. But one suite contains three bedrooms with a floor area of 120 m^2, while the other is a 50 m^2 bachelor suite. Converting the airtightness value to ACH50, the larger suite becomes 5.73 ACH50 and the bachelor suite with a smaller volume-to-surface ratio seems much leakier at 7.02 ACH50. Therefore, users of ACH50 to evaluate the airtightness level of a condominium suit should keep in mind that the results may be biased for different sized suites and those with significantly different geometries (Urquhart et al., 2015).

5.2.2 Normalized Airflow Rate

Normalize airflow rate is calculated by dividing the total air leakage rate by the surface area through which the leakage occurs. Normalized airflow rate presents an averaged airtightness without the variance of space volume and geometry. It is useful when comparing two test spaces with significantly different geometry and volume. Most of the airtightness requirements and codes for commercial buildings are stated in this metric, noted as L/s/m^2 or CFM/ft^2 at 75 Pa. In this paper, normalized airflow rate is recommended to be the metric for airtightness measurement for tall residential buildings.

5.2.3 Leakage Area

There are three metrics containing the phrase "leakage area." The first is *equivalent leakage area*, which describes the size of sharp-edge orifice that would generate an airflow at 10Pa equivalent to that measured in a leakage test. It is used in the CAN/CGSB 149.10 standard (CAN/CGSB, 1986). The second, *effective leakage area*, is the same as the equivalent leakage area but at 4Pa, as mandated in ASTM E779-10 (ASTM, 2003).Neither metric is helpful in suite comparisons since they do not account for the total surface area to put the leakage area in context.

Hence, a third metric, *specific leakage area*, is calculated by dividing the equivalent or effective leakage area by the enclosure area, similar to the normalized airflow rate. One literature argues that normalized leakage area (specific leakage area in this context) is beneficial over other metrics since it allows a direct comparison among different tested spaces (Urquhart et al., 2015). But it might not be an ideal airtightness metric.

Take CAN/CGSB 149.10 as an example. The specific leakage area is calculated based on the total airflow at 10 Pa. The flow rate at 10 Pa cannot be directly measured since 10 Pa is often too small to overcome other driven forces such as stack or wind pressures. Instead, the flow rate is estimated by developing a regression equation based on airflows measured from 50 Pa to 15 Pa (CAN/CGSB, 1986). Compared to the normalized airflow rate, specific leakage area increases errors might be introduced during the regression process and extrapolation process.

5.3 Inconsistency in Normalized Surface Area Calculation

Enclosure area refers to the surface area of the boundary that separates the indoor environment from the ambient. Nonetheless, its interpretation can vary quite significantly (CMHC, 2001) to include only the exterior wall surface area to including roofs and foundations. Only the wall was used in some of the earliest applications, presumably because the leakage through foundation and roof sections is sufficiently small or negligible. In Great Britain and the United States, the surface area of exterior walls and roofs were used for similar reasons. In some cases, floor areas were used rather than enclosure areas. Commonly, the normalized leakage data is stated without an accompanying definition of enclosure area.

For a building tested according to the whole building test, it is the entire building envelope surface area (four exterior walls, roof, and foundation), that should be used to normalize the result. For guarded blower door tests, the exterior wall surface area for the suite is the only leakage section. Some articles also mentioned that whole building test was conducted on the suite or floor level only, in which case the total six sides of surface area of the suite or floor would be a reasonable value for normalization. However, in practice, the normalized surface area is often mismatched according to the airtightness testing method. One report characterizing the leakage rate of existing large buildings, different normalizing areas were used, skewing the results and making comparisons unreliable (CMHC, 2001).

6 Conclusions

Stack effect occurs in all types of buildings in cold climates. It becomes much significant in tall residential buildings because of the building height as well as the floor layout. The implementation of operable windows and balcony doors makes the control of stack effect induced airflows and pressures much difficult. This paper identified and investigated the critical issues related to stack effect in tall residential buildings. Commonly mentioned in the literature, these problems are migration of fire smoke, malfunction of elevator/stairwell doors, and inefficient ventilation system.

A number of stack effect mitigation strategies noted in literature were identified and analyzed. Compartmentalization, a promising passive strategy, can effectively redistribute pressures and reduce air flows induced by stack effect. By improving the airtightness of both internal and external partitioning, each suite can be isolated from the other spaces on that floor and on adjacent floors. The isolation of living units can reduce typical MURB problems, such as cross-contamination of odors, indoor air quality, and energy consumption. An early stage simulation has confirmed that compartmentalizing a building was able to control the impact of occupant behavior, which is a significant contributor to stack effect problems in residential buildings.

When examining the implementation of compartmentalization in existing tall MURBs, no test data were available for the buildings within the research scope. The lack of airtightness information prevents substantial conclusions to be drawn on the success of compartmentalization. This paper then investigated the difficulties in acquiring airtightness data for tall residential buildings. The insufficient data are mainly due to:

- The lack of proper airtightness testing method specifically designed for tall residential buildings;
- The lack of a uniform metric for direct comparisons from different field testing measurements and
- The lack of a uniform definition of normalized area, and clearly documented information of the tested buildings.

7 Recommendations and Future Steps

This paper provides two recommendations to develop a comprehensive understanding on the compartmentalization strategy as a solution to stack effect in tall residential buildings.

The first step is to further investigate the effectiveness of compartmenting a residential building. Although the computer modeling by a software called CONTAM has done in 1996, the change in airflows and pressure differences was simulated base on replacing suite entrance doors and elevator landing doors. However, it is still required to quantify the relationship between the improvement on airtightness and the reduction in stack induced pressures and airflows. Currently, there are several airtightness targets for building exterior envelopes or suite enclosures suggested by building design codes or best practice programs. Those airtightness requirements can be utilized as the inputs to the simulation. Through computer modeling, the relationship between the change in stack induced pressure and airflows corresponding to different building airtightness can be evaluated.

Other future work revealed by this paper is to develop a standardized airtightness testing procedure specific for tall residential buildings. The purpose of this recommendation is to ease the field measurement process so that more airtightness data of tall residential buildings can be acquired for analysis. This paper suggests that the suite/floor level blower door test over other airtightness testing methods. It appears to be the most promising solution because it resolves limits of whole building test on large buildings, as well as avoids the sophisticate operation from guarded blower door test. Moreover, for new constructed buildings, the suite/floor level airtightness test can be integrated into the construction schedule, and the experience in airtight construction can be evaluated and transferable to the later construction work in higher floors.

The suite/floor level blower door test has been used in the literature, however, there is no standard protocol specific for it in tall residential buildings. Provisions, such as the location of blower fan to install, and either or both de- and pressurization are required, need to be standardized to minimize errors occurred in the testing process. To promote the compartmentalization approach, it is important to provide practitioners a feasible and simple tool to assess the airtightness a building has achieved.

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Application of Water Curtain for Blockage of Fire Spread

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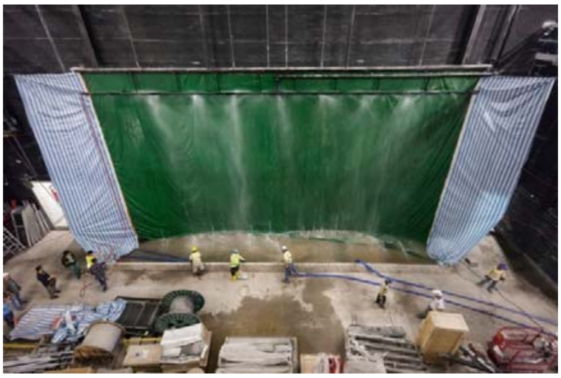
ABSTRACT

This paper presents the results of application of water curtain system for blockage of fire spread as it is widely used in fire protection of lives and properties in Hong Kong. By using the system, water is discharged in the form of a linear curtain for protection against internal or external exposure to fire spread; or as a fire separation barrier between the fire side and the non-fire side. Many studies on the physics and chemistry of the water curtain in fire protection conducted by the researchers and scientists in the past both experimentally and academically, provide valuable results and findings.

The relationship amongst the operating physical factors for the water curtain in radiation attenuation is investigated and general equations on their co-relation are established. Computational Fluid Dynamics (CFD) is adopted to identify the radiation intensity. Radiation attenuation performance by water curtain system is defined by the radiation attenuation ratio when there is or there is no water curtain protection under different designed fire scenarios. Multiple regression analysis is used to evaluate the coefficient and power factors of the variables in the derived formula. Data test is also conducted to verify the formula for the prediction of radiation attenuation by water curtain. The result shows that water curtain performs well in the attenuation of radiation from fire.

INTRODUCTION

For the protection of building opening across compartments, water curtain system is commonly used in Hong Kong (Figure 1). It is a system that discharges water in the form of a linear curtain for protection against internal or external exposure to fire spread; or as a fire separation barrier between the fire side and the non-fire side (Benbrik et al., 2011). To meet the requirements and based on the local building codes (Buildings Department, 2011), the total opening areas for protection or areas of separation in buildings have to be designed and in general according to the local fire code (Fire Services Department, 2012), normally by a water curtain system which requires that for every square metre of opening protection, 10 litres of water should be discharged every minute for half an hour at minimum for the system design.



(i) Compartmentation at Theatre (Leisure and Cultural Services Department, 2017)

(ii) Protection of Firefighter

(iii) Public transport interchange (Lau, 2006-2009)

Figure 1. Application of water curtain

A water curtain system is mainly comprised of open drencher nozzles, piping and a deluge valve (FOC Rules, 1954; Australian Standard, 2005). The system piping is set at the atmospheric pressure. Prior to discharge there is no water in the piping on the downstream of the alarm valve. The deluge valve controls the system water supply. When it is activated by a fire detection system, pilot sprinklers or manually, it discharges large quantities of water automatically over specified areas in a relatively short period of time. As water reaches each open nozzle, it is immediately discharged in the form of a linear curtain to the protected areas (Figure 2). The system is also designed to protect facilities in which significant amounts of combustible materials are stored against fires that grow and spread rapidly. The uses of water curtain system can be further categorized into three main groups, they are fire spread prevention, compartmentation and fire resistance enhancement / strengthening of fire shutters.

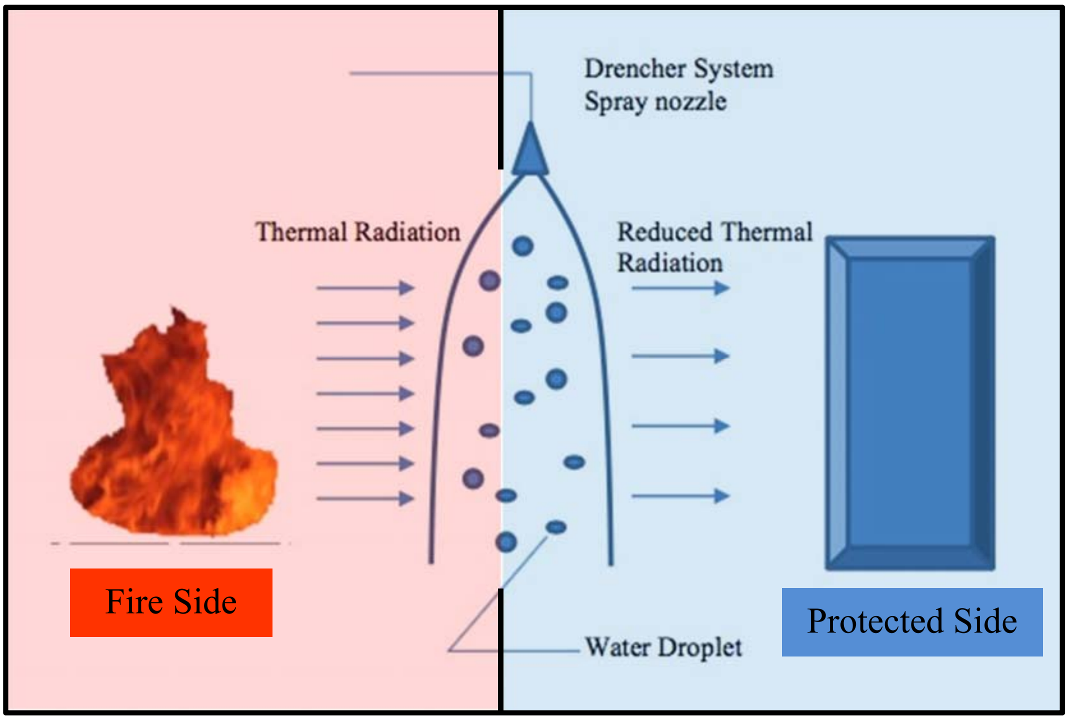


Figure 2. Illustration of protection by water curtain (Chow and Ma, 2006)

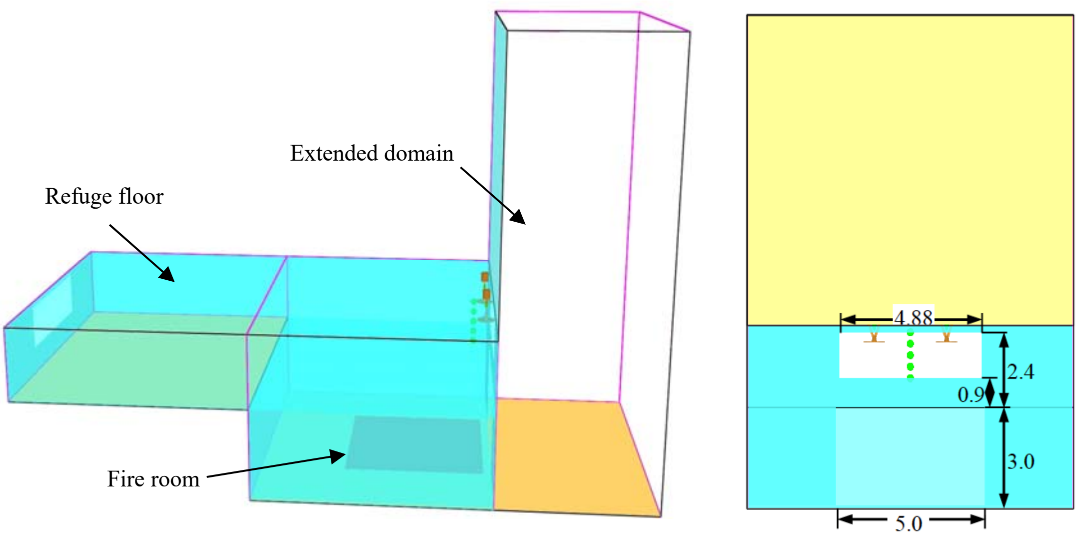
There have been plenty of studies on the physics and chemistry of the water curtain in fire protection conducted by the researchers and scientists in the past both experimentally and academically, providing valuable results and findings (Coppalle et al., 1993; Grubits, 1985; Fong and Chan, 2001: Fong et al. 2001). For the purpose of this study, protection of an external wall opening of a refuge floor by water curtain in a supertall building is selected (Chow and Ma, 2006; Chow and Ip, 2008). The relationship amongst the operating physical factors for the water curtain operation in radiation attenuation is investigated and a general equation on their co-relation is established (Pretrel and Buchlin, 1996). Fire Dynamics Simulator (version 5.5.3 2010) (McGrattan, 2010) is adopted to identify the radiation intensity acting at the external wall opening of the refuge floor from fire sources of different magnitudes from an immediate below floor. The water curtain is operated under different physical factors and different designed fire scenarios. The radiation attenuation performance of water curtain is defined by radiation attenuation ratio at the measuring points when the openings are or are not being protected by water curtain under different designed fire scenarios (Chow and Ma, 2005). Multiple regression analysis is used to evaluate the coefficient and power factors of the variables in the derived formula. Data test is also conducted to verify the formula for the prediction of radiation attenuation by water curtain.

CONFIGURATION OF SIMULATION

By using the FDS, the configuration of the sturcture is required to determine prior to the simulation. The structure consists of two storeys. The lower storey is a 9m (L) x 11m (W) x 3m (H) fire room with an opening 5(W) x 3(H) m^2. Immediate on top of it is a refuge floor measuring 18m (L) x 11m (W) x 2.5m (H) with a 4.88m x 1.5m opening. There is a parapet wall of 4.88m (W) x 0.9m (H) at the external wall opening of the refuge floor. Above the refuge floor is a 9.5m tall façade, which allows fire plume to spread upwards. An external wall opening is designed on the opposite side to enable cross ventilation on the refuge floor which is a requirement in the local building code. Two water curtain nozzles (drencher heads) are installed at the opening and is 2.44m apart (Figures 3 and 4).

Five measuring points are positioned above the parapet wall (ranging from 0.9m above finished floor level (AFFL) to 2.4m AFFL with spacing of 0.35m) at the refuge floor to capture the received radiation from the fire plume spreading from the fire room below the refuge floor. They are placed at a distance of 0.45m from the water curtain and 0.75m from the exterior wall opening.

With the assumption of no wind situation, a 15 MW fire from the immediate floor (fire room) below the refuge floor is set. The water curtain nozzles (drencher heads) have a common k-factor of 30.3. Other parameters are mean diameter of water droplets sizes of 500, 750, 1000, 1500; 2000 μm; spacing between nozzles of 0.8, 1.0, 1.2, 1.6, 2.4 m; and pressure at nozzles of 0.5, 1, 2, 4, and 8 bars. Totally 125 simulations with water curtain protection and one simulation without water curtain protection are conducted to evaluate the radiation intensity under the designed fire scenarios, i.e. totally 126 simulations were conducted.



(a) Perspective View (b) Front View

Figure 3. FDS model (Two nozzles with maximum spacing of 2.44m)

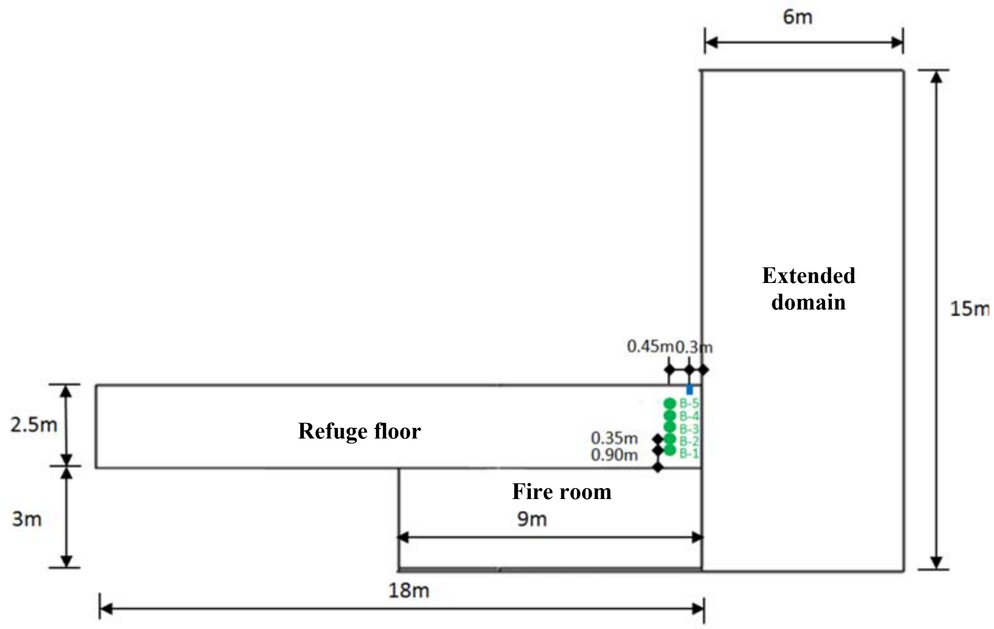


Figure 4. Dimensions of the model and the locations of the measuring points

MATHEMATICAL MODEL FOR RADIATION ATTENUATION PERFORMANCE OF WATER CURTAIN

The radiation attenuation ratio is given by:

$$\xi = \frac{I_0 - I}{I_0} \tag{1}$$

Where

ξ: Radiation attenuation ratio at the measuring points (radiation receiver)
I_0: Incident radiation intensity at the measuring point without the protection of water curtain;
I: Incident radiation intensity at the measuring point with the protection of water curtain;

Factors affecting the radiation attenuation by the water curtain include:

S: Spacing between nozzles (unit: m)
P: Pressure of each nozzle (unit: bar)
D: Mean diameter of the water droplet (unit: μm)
ρ: Density of media (unit: kg/m^3).
Q: Flow rate per unit area at the external wall opening of the refuge floor (unit: l/min/m^2)
W: Width of external wall opening of the refuge floor (unit: m)

H: Height of external wall opening of the refuge floor (unit: m)
K: the k-factor of the drencher heads.

As water is the unique firefighting media being applied, and the density ρ is a constant value of 1.0×10^3kg/m^3, therefore, it will not be involved in the analysis.

In addition, the flow rate of the water curtain is governing by:

$$Q = \frac{Tranc\left(\frac{W}{S}\right)\times\left(K\sqrt{P}\right)}{W\times H} \tag{2}$$

Where 4.88 m is the width of the opening where two drencher heads are installed and 1.5 m is the height of the opening. *K* is the k-factor of the drencher heads.

Since Q is a dependent on the other variables S and P, it cannot be regarded as independent variables and will not be involved in the analysis.

Finally the factors for consideration are the spacing of drenchers *S*, the operation pressure *P* and the diameter of the water droplet *D*.

RADIATION ATTENUATION MODEL

In order to investigate the maximum performance of radiation attenuation by the water curtain, an equation is established and the relationship amongst the depending variables is expressed and represented by the following equation:

$$\xi = A \cdot S^a \cdot P^b \cdot D^c \tag{3}$$

where

ξ: Radiation heat attenuation ratio at the observed point ($\xi = \frac{I_0 - I}{I_0}$)
I_0: Incident radiation intensity at the measuring point without the protection of water curtain;
I: Incident radiation intensity at the measuring point with the protection of water curtain;
S: Spacing between nozzles (unit: m)
P: Pressure of each nozzle (unit: bar)
D: Mean diameter of the water droplet (unit:μm)
a, b, c: are power coefficients in the formula
A: Constant coefficient

From equation (3), apply natural logarithm to find the coefficients in the formula, the equation becomes:

$$\ln(\xi) = C_0 + aln(S) + bln(P) + cln(D)) \tag{4}$$

where $C_0 = \ln(A)$

Multiple Regression Analysis

Since there are totally three factors that may affect the variable $\ln(\xi)$, multiple regression analysis is adopted to formulate the equation and to demonstrate the statistical relationship between the three independent variables (i.e.$ln(S)$, $ln(P)$ and $ln(D)$ and the dependent variable ($ln(\xi)$ in equation (4) (Ronald et al., 2007).

In the output (Table 1), it is found that the adopted three variables are significantly associated with the dependent variable with the p-value approaching zero. Given the common significant level of 0.05, it can be concluded that the three variables are statistically significant.

Table 1. Estimated Coefficient for Equation (5)

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	47.731	15.910	957.904	0.000
Residual	121	2.010	0.017		
Total	124	49.740			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Co	4.1130	0.164	25.151	0.000	3.789	4.437
ln(S)	-0.5816	0.030	-19.278	0.000	-0.641	-0.522
ln(P)	0.3667	0.012	31.184	0.000	0.343	0.390
ln(D)	-0.9182	0.023	-39.110	0.000	-0.965	-0.872

Residual Plots

According to the residual plots in Figure 5, it shows that the plots are in random pattern indicating a good fit for a linear model.

Regression analysis to determine the maximum attenuation ratio

From equation (4) $\ln(\xi) = C_0 + aln(S) + bln(P) + cln(D)$

From the regression analysis result, the coefficient of determinant R^2 is 0.96, which implies a good fit of linear relationship. The formula for the maximum attenuation ratio is established as below:

From Table 2

$$\ln(\xi) = 4.1130 - 0.5816ln(S) + 0.3667ln(P) - 0.9182ln(D) \quad (5)$$

Applying exponential to the both sides of equation (5), the maximum attenuation ratio (ξ) is obtained and represented by the following equation:

$$\xi = 61.1327 \cdot S^{-0.5816} \cdot P^{0.3667} \cdot D^{-0.9182} \tag{6}$$

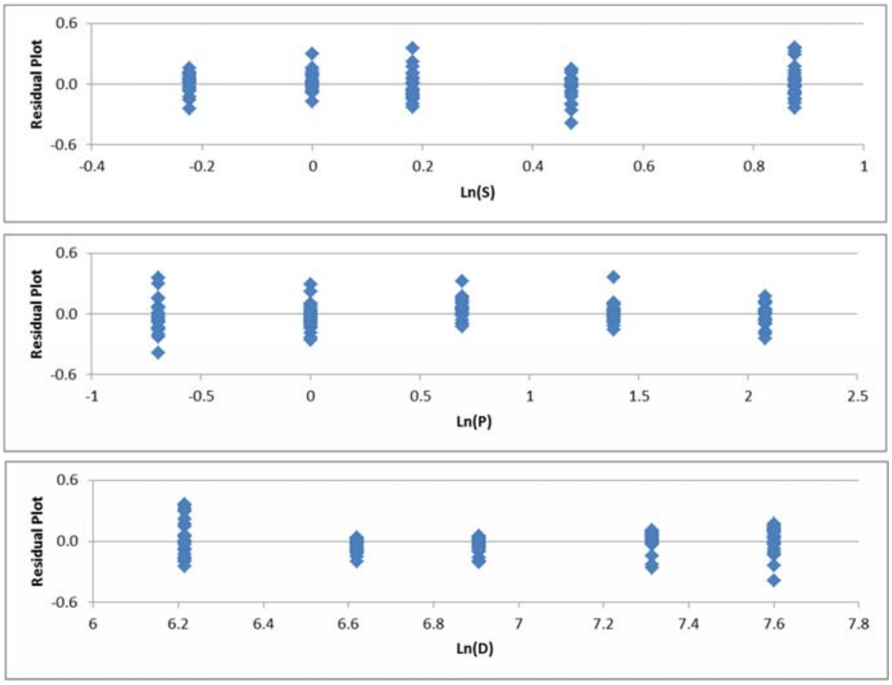


Figure 5. Residual plots of the three parameters with the residual

DISCUSSION OF RESULTS

Radiation attenuation data are recorded from the five measuring points (B1 – B5). Radiation attenuation ratios are evaluated from recorded data which are generated in different designed fire scenarios when there is or there is no water curtain protection at the external wall opening of the refuge floor i.e.(Io – I)/Io (Equation 1 and Table 2 refer).

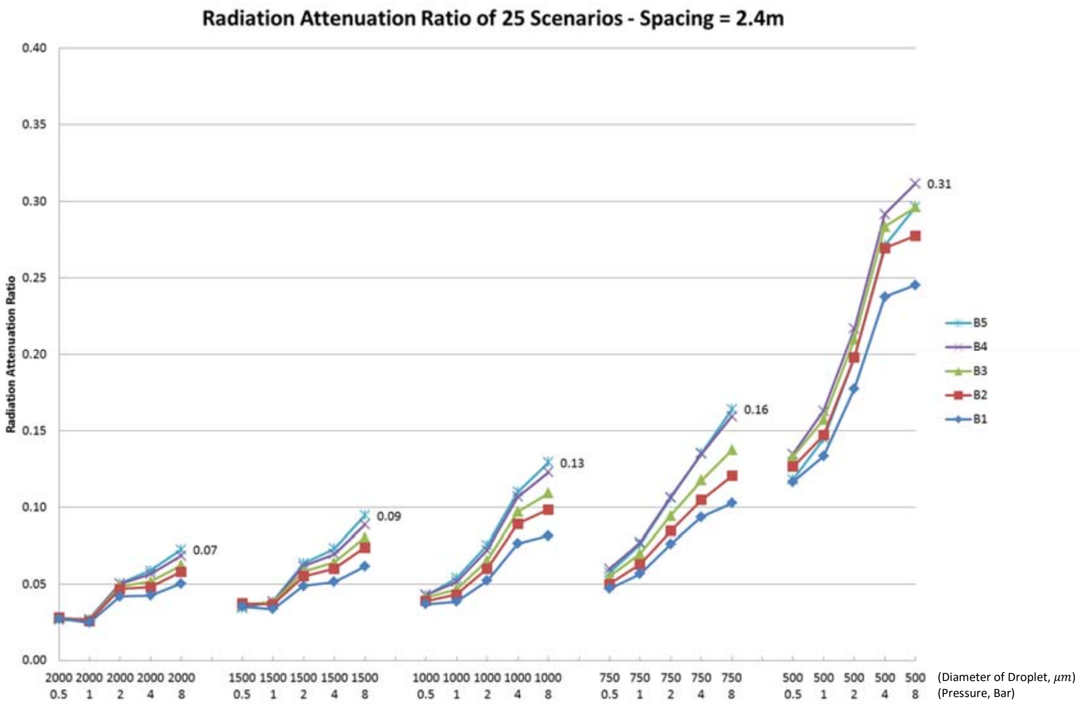
Table 2. Summary of the radiation attenuation ratios

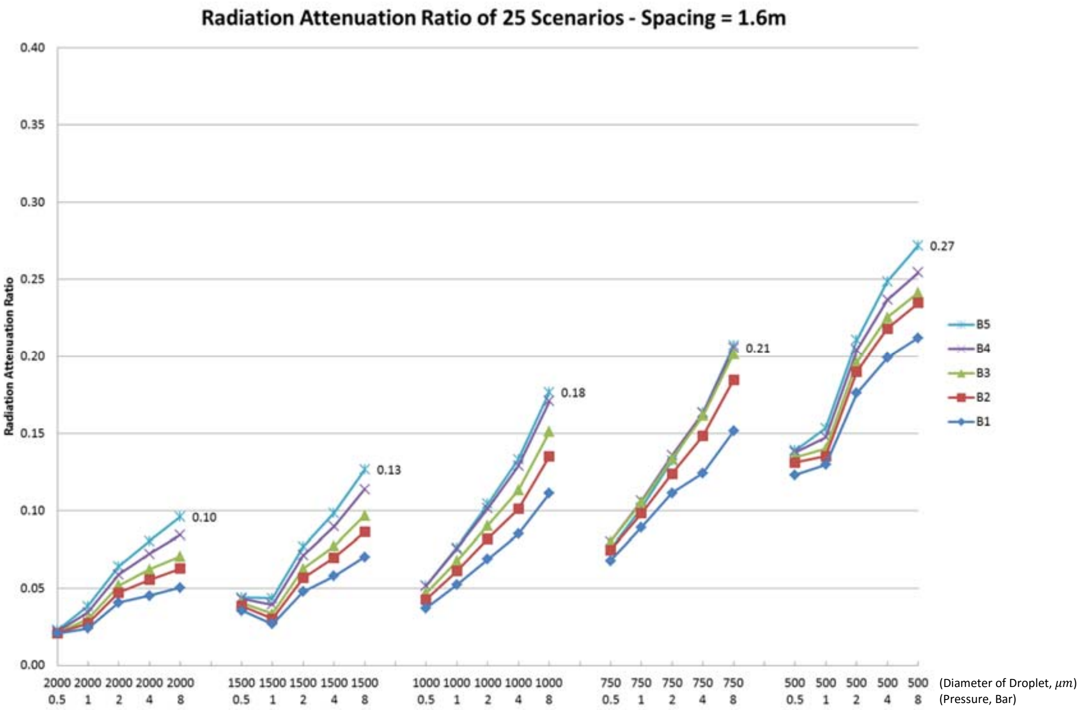
Measurement Point		Min	Max	Average	Std.
Attenuation Ratios of 125 Scenarios	B-1	0.0207	0.2755	**0.0976**	0.0590
	B-2	0.0208	0.3385	**0.1146**	0.0697
	B-3	0.0210	0.3722	**0.1241**	0.0748
	B-4	0.0218	0.3870	**0.1343**	0.0797
	B-5	0.0228	0.3838	**0.1391**	0.0817

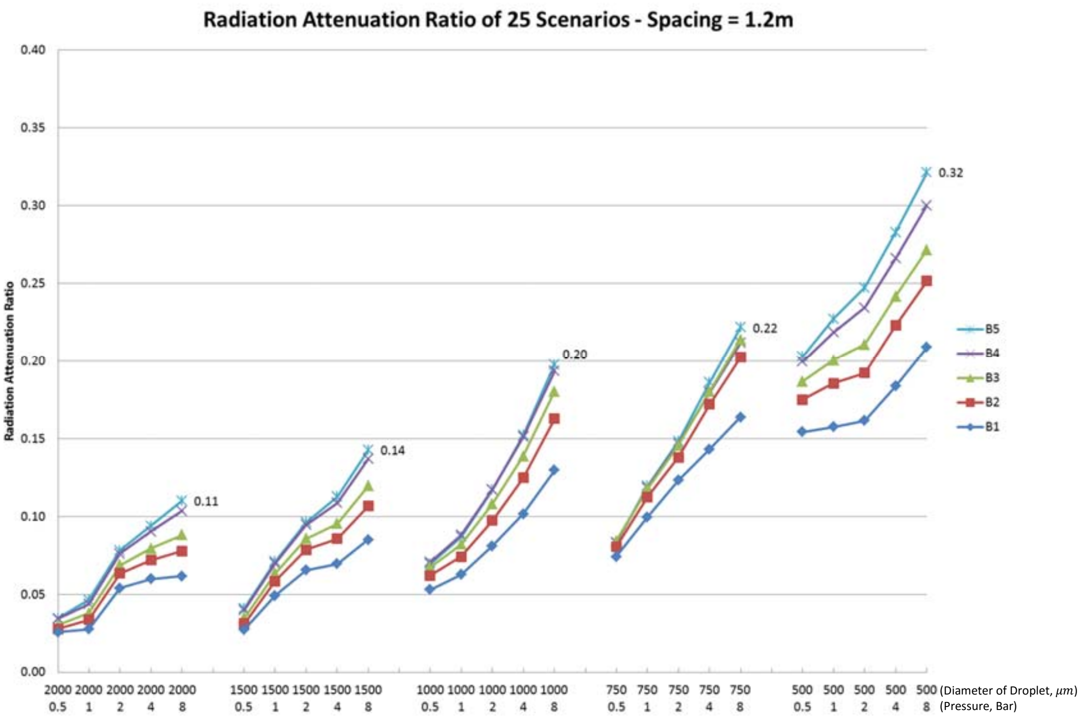
The result shows that measuring point B5 has recorded the highest averaged attenuation ratio of 0.139. The second highest is 0.134 at point B4. The remaining values are in descending order and the smallest is 0.098 at B1. For the scenarios with water curtain protection, the water droplets discharge from the nozzles will be at higher pressure and a more steady flow rate at the upper portion than the lower portion of the water curtain. The upper portion of the curtain gives a better shielding effect and accounts for the highest radiation attenuation ratio. The radiation performance of water curtain is shown in Figure 6. By fixing the nozzles distance, the attenuation ratios are plotted against the pressures and the water droplet sizes. It is found that there is a trend, for nearly all cases, the attenuation ratios become larger when there is an increase in the water pressure, decrease in nozzles spacing and decrease in water droplet sizes.

It is also noted that:

i) Smaller mean diameter of water droplet increased significantly with the radiation attenuate ratio;
ii) At the lowest measuring level, the averaged radiation attenuation ratio is the smallest; and
iii) At the highest measuring level, the averaged radiation attenuation ratio is the largest.




Radiation Attenuation Ratio of 25 Scenarios - Spacing = 1.6m
Radiation Attenuation Ratio
0.10
0.13
0.18
0.21
0.27
B5
B4
B3
B2
B1
(Diameter of Droplet, μm)
(Pressure, Bar)


Radiation Attenuation Ratio of 25 Scenarios - Spacing = 1.2m
Radiation Attenuation Ratio
0.11
0.14
0.20
0.22
0.32
B5
B4
B3
B2
B1
(Diameter of Droplet, μm)
(Pressure, Bar)

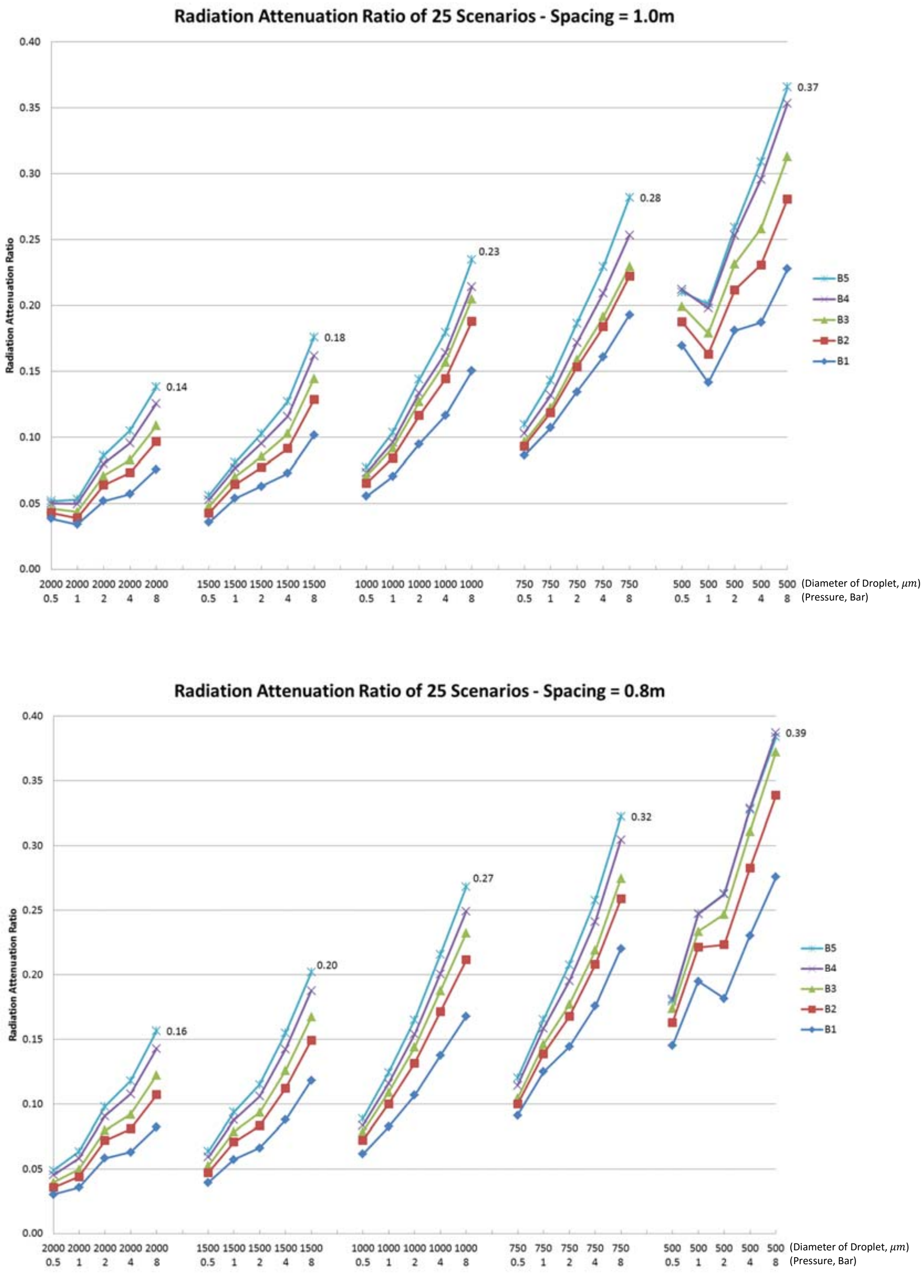


Figure 6. Radiation attenuation performance of water curtain with different nozzles spacing

CONCLUSION

Undoubtedly, water curtain is an effective and liable system in the reduction of radiation attenuation values (Chow et al., 2011; Cheung, 2009), the following study results and findings are of value in further studies:

- R^2 indicates good correlation of the prediction using the multiple linear regression analysis for the radiation attenuation ratio;
- Variable “Mean diameter of droplet” and “Drencher spacing” will cause negative influence to the radiation attenuation ratio;
- Variable “Pressure” will cause positive influence to the radiation attenuation ratio; and
- To look for the maximum attenuation ratio by changing the parameters of the general equations based on the equation 3 can be established by substituting the unknowns A, a, b, and c to the equation.

Further study should be carried out to demonstrate the application of water curtain for the protection of lives and properties inside the residential unit, e.g. open kitchen and living room, etc. It is believed that the water curtain is an effective and reliable suppression system with limited water damage (Zou et al., 2008), the system is applicable for the congested place with high life risk and high fireload density environment, like Hong Kong.

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Housing Technology for Smart Cities

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ABSTRACT

This paper will present research being conducted to develop sustainable and affordable housing that leverages Population Health strategies for Smart Cities. We are currently developing a multifamily prototype housing unit that demonstrates best practices in aging-in-place strategies and telehealth technology. We are also investigating prefabricated construction methodologies that will be utilized to bring plug-and-play technology infrastructure to the exploding senior housing demographic.

Gigabit networks allow Smart Cites to collect and analyze vast amounts of data. This data is like a new kind of natural resource; one that will have as much impact on the way we plan cities as water and electricity did one hundred years ago. (KCUR, 2017)

Sensors embedded in the built environment are able to collect such information as:
- Human Vital Signs (heart rate, breathing, body temperature, weight, blood pressure, hydration)
- Physical Activity (Activities of Daily Living, falls, gait, sleep)
- Environmental Factors (temperature, humidity, air quality, water quality, weather)
- Pharmaceutical Regiments (over dosing, missing doses)

Population Health strategies utilize the collection and analysis of such data to deliver health care more affordably, affectively, and sometimes before we know we need it. Some of the more advanced technologies will include: Motion Sensors/Fall Detection, Gait-Analysis (determination of early onset Alzheimer's and Parkinson's), Automated LED Smart-Spectrum Lighting (optimizing circadian rhythms), Smart Mirrors, Smart Toilets (hydration monitoring/diuretic dosage), Sleep Sensors (ballistic cardiogram), and Automated Medicine Dispensers (coupled with Smart Toilet for heart medication).

INTRODUCTION

In 2012 it was announced that Google Fiber was coming to Kansas City. (Loria, 2012) This would be only the second gigabit network installation in the United States. Chattanooga had been the first in 2010. (Wyatt, 2014) A robust tech startup ecosystem has flourished with the potential advantage that comes with "unlimited bandwidth." Several symposia and summits have been held exploring the implications of ubiquitous connectivity of the Internet of Things and Kansas City's website boasts that it is, "the world's most connected Smart City." (kcmo.gov/smartcity, 2017)

While many gigabit networked cities tout their entrepreneurial friendliness and potential for economic growth, the true promise of gig-speeds may be Population Health strategies. (Gigtank, 2016) Instrumented environments have the ability to collect a wide range of biometric data. The collection and analysis of such data to deliver health care more affordably, affectively, and sometimes before we know we need it. Even more potent may be the impact on health, wellness and general livability when this biometric data is aggregated with all the vast amounts of data a Smart City can collect. (Halegoua, 2015)

The connectivity of sensors, devices, and environment through the Internet of things requires a re-examination of the role that architects and planners can play in shaping cities that are data-driven. In particular, the housing unit; its design, fabrication, delivery, and maintenance must leverage instrumentation that can allow all citizens to connect and participate in the Smart City.

SMART CITIES

There exist as many definitions for Smart Cites as there have been Smart City conferences. One generally associates the term with a government-driven effort to synchronize the core functions of a city through data collection and actionable analysis. Neiroti et al. have looked at 70 cities and outlined the following primary categories: natural resources and energy, transport and mobility, buildings, living, government, economy, and people. (Neirotti et al., 2014)

The Smart City movement has the potential to improve the lives of billions of people living in urban environments on this planet. Perhaps seen as a more globalized and systematized approach to Smart Growth initiatives of the 1990's, Smart City proponents argue that coordinated and connected systems will improve the livability while dramatically reducing resource consumption.

We seem ever closer to the promise of driverless cars, drone deliveries, and stylized utopian urbanscapes. And yet, the digital divide continues to leave marginalized communities behind. Impoverished and disenfranchised neighborhoods existing in the "data shadow" remain unable to align basic services with the livability we expect from a so-called Smart City. (Leonelli, S., Rappert, B. and Davies, G., 2017)

One is reminded of the altruistic intentions of the Modernist movement and LeCorbusier's mass produced 'House-Machine' of early last century. (Le Corbusier, 1931) While our expectations for housing have moved beyond notions of white box machines for living, the lasting legacy of Modernism is still the social project. Smart and connected cities have the potential to *restructure* the world and allow us to act critically and strategically within a society we cannot completely remake.

The Smart City must operate in a way that allows us to make headway on the great challenges of our time: climate change, crumbling infrastructure, lack of access to clean drinking water, food insecurity, disaster response, security from terrorism, refugee shelter in areas of conflict, and homelessness. (Goodspeed, 2015)

NEED

By 2050 the global population will be nearly 10 billion people with nearly 70% of those living in urban areas. (United Nations, 2015) Smart Cities with gigabit networks and connected services will be ubiquitous. And yet, affordable dignified housing that is able to leverage the connectivity of Smart Cities will become increasingly elusive for many. This integrated and connected vision of urbanity will not be realized unless we invent new ways of organizing our cities and fabricating our buildings.

Despite the sea change in technology all around us, we continue to construct buildings the way we did fifty years ago. Prefabrication, through optimized manufacturing processes is rarely applied to large-scale urban structure. Fabrication techniques, and particularly digital fabrication techniques, allow us to take a construction process we used to call "rough framing" and fabricate assemblies with the precision of a medical device.

These tolerances, applied to multifamily housing, allow us to activate Population Health strategies. Rising healthcare costs, an exploding aging population, demographic shifts from rural areas to urban areas, and a shortage of affordable housing make for a potent opportunity to transform the way we build urban environments. Re-imagining this data-driven built environment will require a multidisciplinary team of architects, planners, engineers, health care professionals, academic researchers, and industry partners to bring the potential of this instrumented built environment to society both equitably and at scale. These new housing models can improve the quality of life for all citizens.

DEMOGRAPHICS

Technology-rich prefabricated smart housing can also address shifting needs brought on by shifting demographics. American cities are incredibly unprepared to house the wave of Baby Boomers that are turning 65 at a rate of 10,000 per day. (Pew Research Center, 2010) The escalating cost of assisted living and health care costs associated with the aging will require us to re-think the way we deliver health and wellness services. (Pfeifer, 2016) The housing prototype presented here shifts some of the care and monitoring that occurs in assisted living facilities to the home. This allows for residents to age-in-place longer and at a lower cost than in the existing systems of Continuing Care Retirement Communities (CCRC). The prototype assemblies presented here could also be used to retrofit existing housing stock that is inadequate in addressing the needs of ailing seniors.

SENSED ENVIRONMENTS

Critical to Smart Cities will be neighborhood scale. IoT connectivity will not increase livability of social connectivity is cumbersome. Key to wellness will be the creation of Lifelong Neighborhoods. (Ball, 2012) Lifelong Neighborhood are those where one can thrive at all stages of life: great schools, great parks, walkability, efficient mass transit, access to job centers, various housing options, and proximity to senior health clinics and community centers.

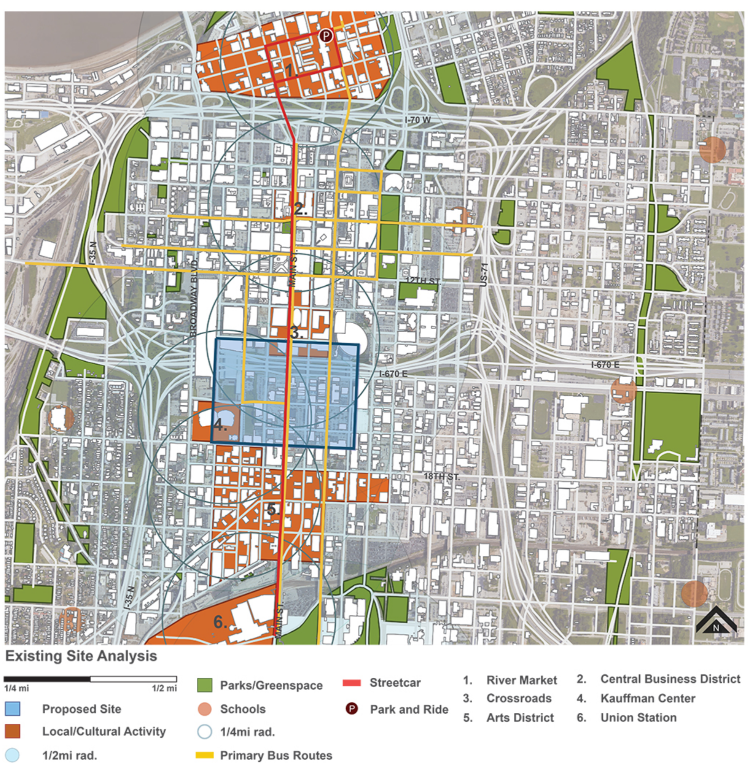

Figure 1. Smart City Master Plan, Institute for Smart Cities, University of Kansas

The scale of housing is also critical. Sensor-enabled multifamily housing must support walkable streetscapes. Complete Streets concepts provide efficient systems of shared roadways and neighborhood-scaled streetscape. (LaPlante, 2007) To the fullest extent possible, housing for Smart Cities should be visitable and designed with adherence to Universal Design Principles.

To be most effective in its deployment Population Health strategies must provide essential new tools to healthcare providers in caring for those most vulnerable in society and linking them to the health services they need – sometimes before they even know they need them. Low Income Housing Tax Credit projects catering primarily to seniors may be a laudable target for sensor deployment. One innovative development model would collect biometric information on residents on site. A ground floor “clinic” or Living Lab could collect data on willing residents and provide associated healthcare services. While this configuration provides various opportunities for public-private partnerships, a housing developer or housing authority could build out this medical office space and rent it to interested health providers, university medical centers and research institutions. The potential for low income projects is enormous. Typically located in rent-depressed blighted neighborhoods, a university needing access to an aging demographic would be willing to pay above market rate rents. This leverage of institutional resources subsidizes the affordable housing and allows for more dignified and sustainable housing.

Another development scenario that we had looked at was the partnering of healthcare networks with senior housing developers to provide sensor-ready units. Also, the ongoing collection of biometric data that leads to actionable health solutions may qualify for Chronic Care Management Vouchers under the Affordable Care Act.

DATA-DRIVEN HOUSING UNITS

There exist several technologies that could transform the way we think about sustainable and healthy environments. Sensors embedded in the built environment are able to collect such information as human vital signs, physical activity, environmental factors, and others. Activity trackers have the ability to detect falls and monitor movements throughout a living unit and also a community. One could track whether an elderly patient has fallen or has gone into the bathroom and not come out for several hours. Someone could be alerted when dementia patients susceptible to confusion leave their apartment or the building complex.

Sleep sensors can be utilized to further monitor health. Groundbreaking work at the University of Missouri’s Tiger Place uses a ballistocardiogram measuring the fluid moving in and out of the heart to monitor hours of sleep, restlessness, number of trips to the bathroom, and sleep apnea. (Rantz, et al, 2013)

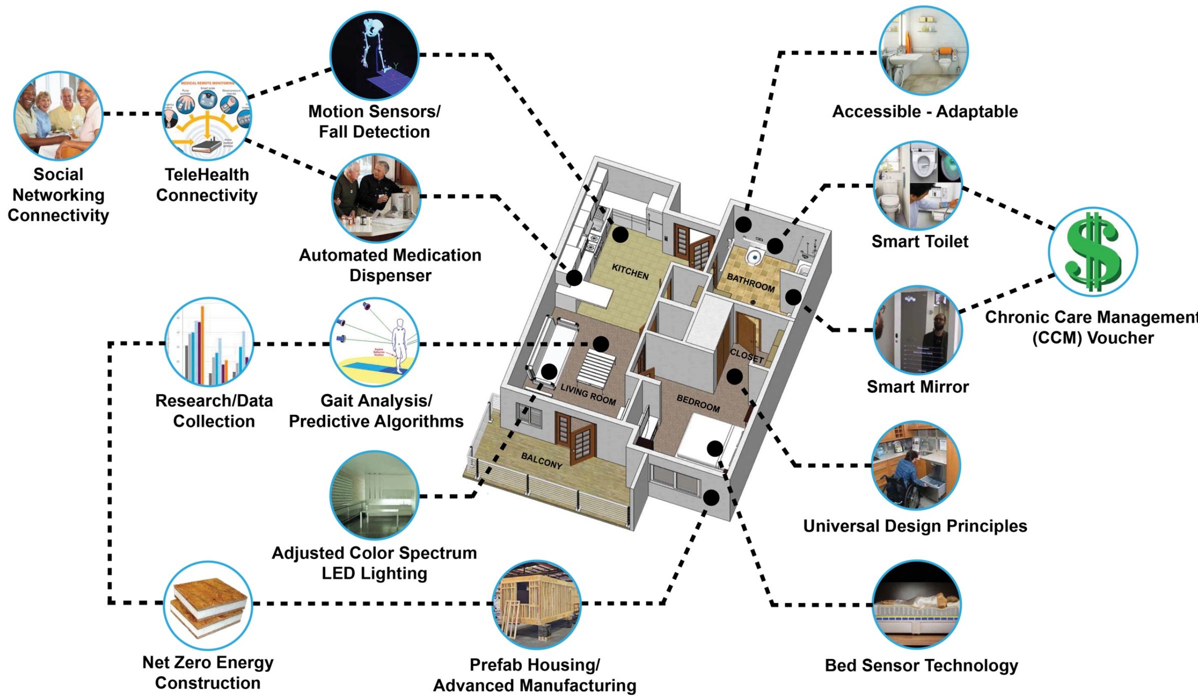

Figure 2. Prototype "Smart" Unit, Institute for Smart Cities, University of Kansas

Smart mirrors on the market today allow one to check the weather and watch the news. We are investigating the ability for such mirrors to track the reflexes associated with eye movement. It can even monitor skin cancer, moles, and plaque on teeth, alerting the resident or health care provider when there is a problem. Soon facial recognition software will be able to detect minute asymmetries in facial muscles that may be an indication of stroke or cardiac condition. (Andeu et al, 2016)

The smart mirror will also meter the yellowing of the eyes as we age. This yellowing of the eyes blocks the wavelengths of light that allows our bodies to re-boot our circadian rhythms each day. (Mainster, M.A. and Turner, P.L., 2013) Tied to custom-color-adjusted LED lighting, this technology will promote circadian health: the production of melatonin in the evening that helps us to sleep and cortisol in the morning to help us wake up. This circadian dysfunction could be contributing to a number of ailments one typically associates with aging: tiredness, disorientation, reduced alertness, even depression. (Tarkan, L., 2012)

Smart toilets have been written about for several years. Accessible today are units that are equipped with heated seat, sanitizing features, and music. The newest generation collect health markers. (Vanni, O. 2017) We are exploring with geriatric pharmacists the ability for a toilet to take hydration and glucose readings. This may provide the best anecdote for explaining the potency of a Smart City: the data could be coupled with that of an automated medicine dispenser to automatically adjust diuretic in heart medication or insulin regiments.

Perhaps the furthest we have been able to take a Smart Home feature has been gait analysis. Research grants from the American Institute of Architects and the Mozilla Gigabit Community Fund have furthered our efforts. We have installed simple accelerometers and strain gauges into a typical wood-framed residential floor and calibrated the sensors to record heel strike. At two-hundred readings per second, the data is not only able to detect a fall but it can record data patterns that may indicate a limp or stagger. The data can be fine-tuned to detect shuffling and even tremor.

The implication is that this “smart floor” could be used to detect symptoms of early onset Parkinson’s and Alzheimer’s disease. We are working with scientists who are developing predictive algorithms capable of processing the patterns of widening stance, often a sign of hydrocephalus, a form of dementia. We are also exploring patterns related to the ball of the foot striking close to the timing of the heel, a potential sign of neuropathy, a symptom of diabetes.

Our work with gait analysis through sensors in the floor is not nearly as accurate as the worn sensors that might be found in a human performance lab, however, they are a fraction of the cost. Also, we are not convinced they provide significantly more data than an Apple watch or a FitBit. Again, at a fraction of the cost, sensors that act in the background of our lives: in the wall and floor assemblies, provide a remote monitoring system that is passive. It can be opted out of and never engaged. It can also be turned on to collect data in the event of a fall or other health problems. It also works for a demographic that may not have the ability to operate smart phones and smart watches or have the desire to log steps or heel strikes online.

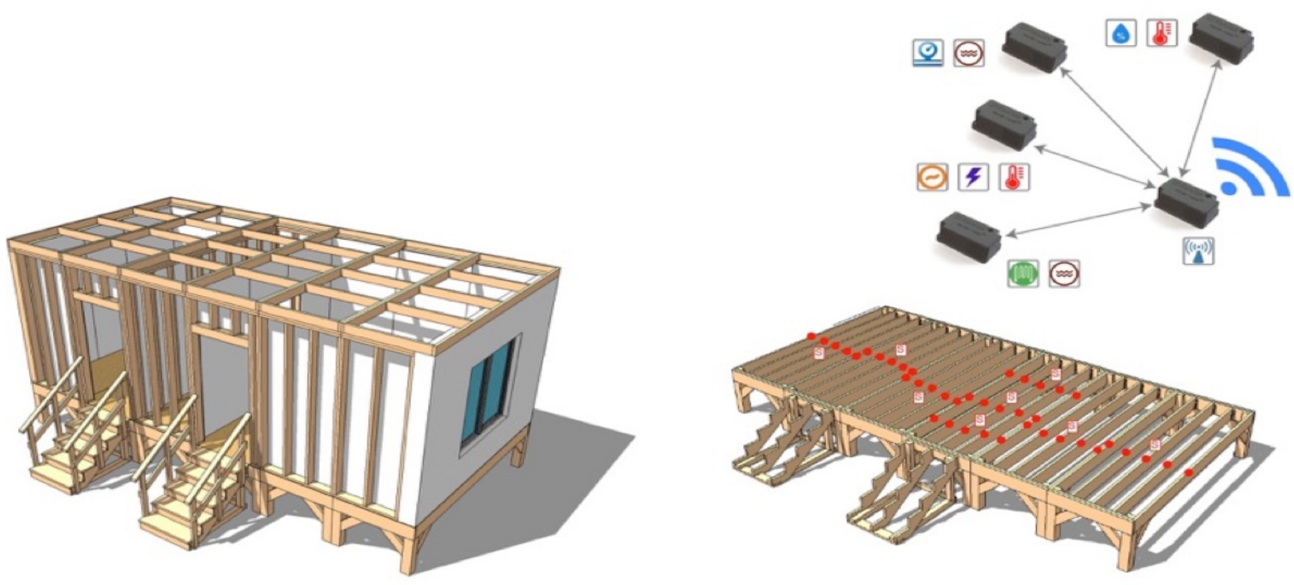

Figure 3. Smart Floor Mock-up

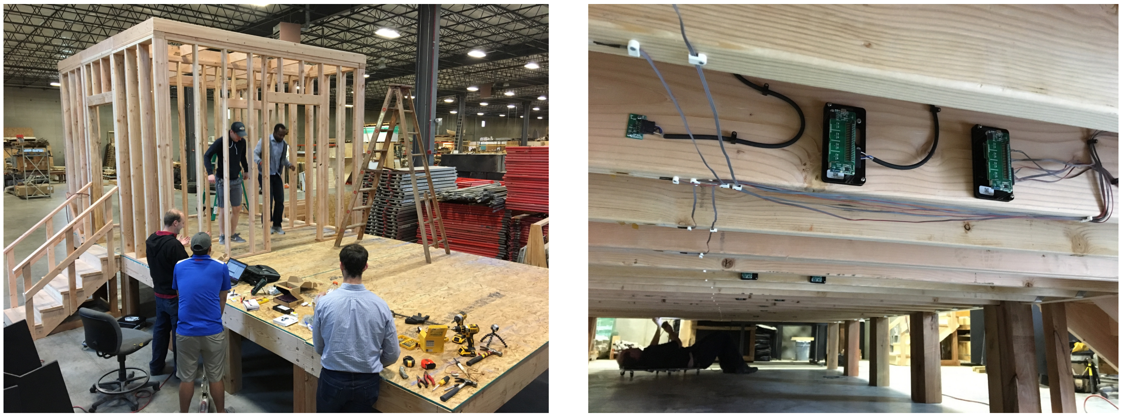

Figure 4. Smart Floor Assembly with accelerometers and strain gauges

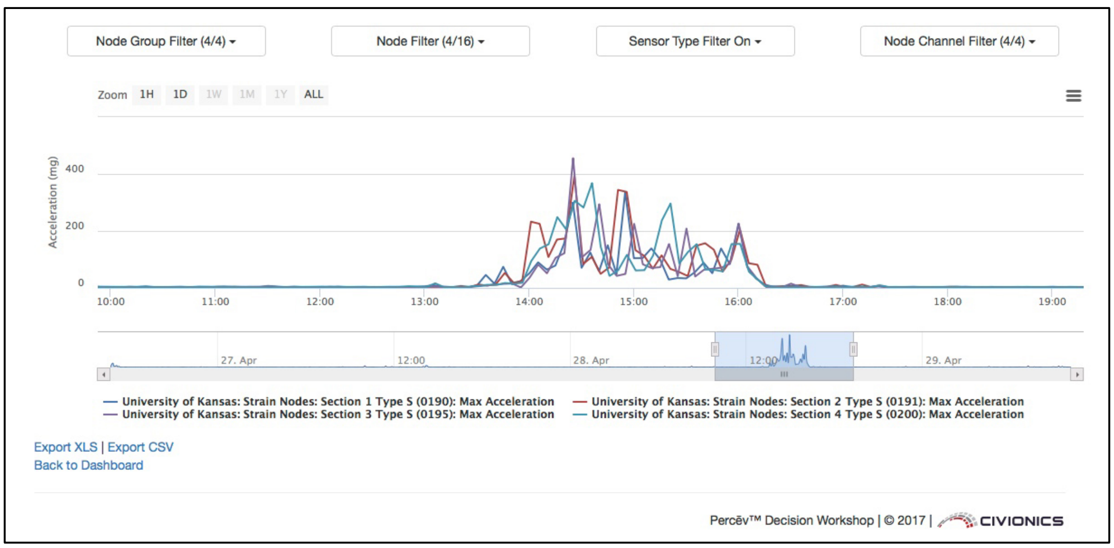

Figure 5. Heel strike data collected for use in gait analysis

MAKING AGGREGATED DATA ACTIONABLE

The incredible potential of a gigabit network enabled Smart City is the aggregation and analysis of this data. For example, say we know that an elderly resident has had only four hours of sleep two nights in a row. His mirror indicates that his eye tracking is off and reflexes may be impaired, gait analysis shows he is favoring his recently replaced hip, and his toilet indicates he is dangerously dehydrated. Now, cross that data against environmental data that is being collected: the forecast calls for freezing temperatures and a light rain, high humidity, and unusually high particulate matter in the air. These data sets may allow us to predict that this elderly gentleman has a 99% chance of falling the next day.

Now imagine that these sensors are imbedded throughout a community of 10,000 housing units and that some minute fraction of that population has a 99% chance of falling the next day. Identifying those 10 – 15 citizens is extremely powerful. An alert could let them, their family, or their caregiver know that they need to take a little extra care the next day or that someone may need to assist them with running their errands. This is the potential of a data-synchronized lifelong community.

SCALABILITY

How does one bring millions of sensor-enriched affordable housing online? We believe the answer lies in prefabrication. Prefabrication allows for optimized manufacturing processes to be employed. Assembly in controlled warehouses provides for more reliable and safer working conditions. (Smith et al, 2017) Pre-fabricated assemblies can also be utilized to adapt existing housing stock into more connected applications.

Utilizing robotic assembly, the construction phase we now refer to as "rough-framing" will achieve tolerances that allow the housing unit to achieve the precision more appropriate to a medical device. Also, energy efficient features such as air-tight construction and high performance building systems enabling net-zero energy usage can be integrated before the assembly arrives at the building site.

Prefabrication saves money by reducing construction time, eliminating waste, and is the only viable solution to bring affordable, dignified, and connected housing to the masses.

Figure 6. Framing table with wood jig; steel jig prototype

MAKING THE THING THAT MAKES THE THING

The University of Kansas maintains a 65,000sf maker space out of which are run our design-build studios. The world-renown Studio 804 run by Distinguished Professor Dan Rockhill also operates out of the facility. A recent housing study conducted with fifth-year architecture students teamed University researchers with industry partners to investigate prefabricated housing techniques.

We are working with a structural building panel manufacturer to optimize the fabrication process for Passive House standards. The prefabricated system includes a traditional wood-framed structural wall, air barrier, continuous exterior insulation, nail base, water-resistive barrier, and preinstalled, air-tightened windows and doors. Students are assisting in optimizing framing table equipment to incorporate a computer automated jig configurations in order to create both prototypical and custom housing solutions.

The panels can be produced in a warehouse at a fraction of the time seen in traditional site-built construction and the advanced manufacturing process will ensure quality control and reduced waste. MAMTC (Mid-American Manufacturing Technology Center) is also advising on the project. MAMTC is a not-for-profit corporation that is supported by a public and private partnership of companies, and the National Institute of Standards and Technology Manufacturing Extension Partnership (NIST MEP). The organization is a part of the US Department of Commerce and its sole purpose is to help companies realize growth in the changing global marketplace through innovation.

We are also currently working with the KU School of Engineering on a Lightweight Modular Steel Floor Systems for Rapidly Constructible and Reconfigurable Buildings. This prefabricated two-way modular system is ideal for embedding sensors. It can be fabricated in a warehouse and craned into place by two attachment points. The modules are configured from standard steel shapes that can be stacked on trucks and shipped to site. (Boadi-Danquah et al, 2017)

The self-supporting nature of the assembly allows for easy deconstruction and reconfiguration. The two-way configuration requires numerous slots to be cut at each intersection and a tack weld to hold the assembly in place. We are working with a local metals manufacturer to accomplish both the slot cuts and the tack welds with robot arms. The speed and accuracy of such a process far outweighs the time and cost of accomplishing these tasks manually.

As a result of its modularity, lightweight, ease of integration of building systems, and sensing components, the smart flooring system promotes reuse and sustainability. Structures employing these modular systems are able to adapt to changing building needs and uses over time.

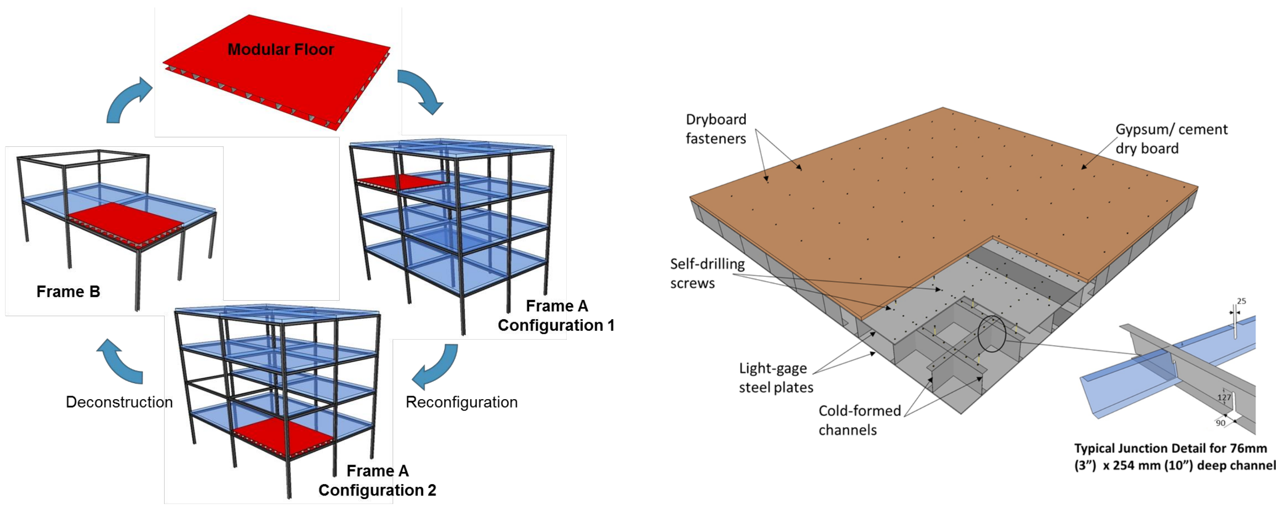

Figure 7. Lightweight modular steel floor system for rapidly constructible and reconfigurable buildings, Fadden, M., Boadi-Danquah, E., and Robertson, B.

CONCLUSION

The notion of Population Health strategies made possible by connected urban environments will require us to reinvent the way we build buildings and organize cities. Population Health strategies link those most vulnerable in our society to the health services they need – sometimes before they even know they need it. Predictive algorithms mine biometric data collected by sensors.

Currently, there are many active (worn) sensors that exist in market products, however, sensors that exist in the background of our lives – protected in walls, floors, and ceilings - are less visible and lend themselves to being installed during the construction process. Optimized manufacturing techniques can result in prefabricated building assemblies that make up sensor-rich environments at scale. Prefabricated units configured into multifamily housing and mixed-use buildings can provide a technology infrastructure that enables plug-and-play health and wellness strategies to be prescribed, monitored, and adjusted by remote healthcare providers.

Once optimized, the housing prototypes can be adjusted to allow for the location-specific construction limitations and available labor practices. Also, energy efficient features such as air-tight construction and high performance building systems enabling net-zero energy usage can be integrated before the assembly arrives at the building site. Prefabrication saves money by reducing construction time, eliminating waste, and is the only viable solution to bring affordable, dignified, and connected housing to the masses.

Finally, it cannot be stressed enough that the health-monitoring technology presented here are secondary to health and well-being. Primary to health and well-being is the safety and security one finds in diverse and vibrant Lifelong Neighborhoods that nurture social connectivity.

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The Longitudinal Impact of Energy Education on Affordable Energy Efficient Multifamily Housing Units

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Keywords: Energy Efficient Housing, Energy Literacy, Affordable Housing

ABSTRACT

The purpose of this study is to better understand the impact of occupant education on energy consumption for energy efficient, affordable housing units. Since 2006, firms and local policies in Virginia have increasingly committed to sustainable housing principles by incentivizing green building certifications, training and construction processes. While efforts have focused on the suppliers of energy efficient homes, occupants, the source of energy consumption in buildings, have been less investigated. Technological energy efficiency improvements are often crippled by occupant behavior such as lack of understanding, improper use, over- consumption, and substandard maintenance. Previous work has studied the relationships between design, construction and energy use and also shown education to be an effective tool in reducing energy use. More work is needed to fully explore the most effective educational processes and their effects on occupant behavior.

In collaboration with Housing Virginia and Viridiant, the Virginia Center for Housing Research is in phase three of a longitudinal study evaluating the performance of 15 multifamily developments at the unit-level to determine influences on the variability of energy usage by residents. Our study will inform residential energy efficiency policies for investments in education, incentives, and building components. In the most current phase of the study, we are focusing on targeted education as a solution for reducing energy consumption. In our broad sample, we found residents who had been educated about technology and energy consumption in their unit consumed 14.8% less energy. To expand on this finding we have an experimental design in progress including a 39-unit subset of our larger data set. While only a few months into the data collection, preliminary findings are promising. Residents who received a targeted education on their energy consumption are saving 25% more energy a month compared to the non-educated residents. In addition to a statistical quantitative analysis, the data we are collecting uniquely utilizes a multi-method approach through interviews and "next generation" energy monitors to reveal the appropriate occupant understanding required to optimize affordable energy efficient housing.

INTRODUCTION

Since 2006, firms and local policy have increasingly emphasized green building certification, training and construction processes and committed to sustainable principles. At the same time, the Virginia Housing Development Authority (VHDA) implemented some of the most aggressive green building standards in the nation within the Low Income Housing Tax Credit (LIHTC) program. VHDA has done this by providing a significant scoring incentive for applicants who choose to develop in compliance with green certification standards. Housing Virginia, EarthCraft Virginia and The Virginia Center for Housing Research (VCHR) at Virginia Tech collected, mapped and modeled correlates across 320 energy efficient LIHTC Virginia units for the following variables: 1) estimated energy usage, 2) actual energy usage, 3) incorporated construction technologies and 4) resident behavior. Actual energy usage for developments in the study was 16.6% less than estimated and approximately 30% less than new standard construction. Resident behavior among units was striking in its variability (Zhao et al. 2017), which lead to the finding that education of residents is the next step in reducing energy usage variability.

The Department of Energy explicitly states the importance of energy-literate occupants when utilizing a whole-house systems approach to developing efficient housing. To cost-effectively reach efficiency goals, a balance must be upheld between design, construction and occupant behavior. Multiple studies have shown the need, effectiveness, and demand for energy efficiency improvements in the residential sector (Ehrhardt-Martinez et al. 2010) (Ehrhardt-Martinez and Laitner 2009) (Grosskopf and Kibert 2006) (Dinan and Miranowski 1989). While the realm of residential energy efficiency research is not new, there is still a gap in understanding social and technological phenomenon of efficient residential energy consumption (Laitner and Ehrhardt-Martinez 2009). In the past 30 years, building technologies have become more efficient yet energy consumption trends do not proportionally mimic efficiency improvements (Alliance to Save Energy 2016) (EIA 2013). By strategically using social and technological innovation, energy conservation goals can be met in an efficient manner (DOE 2016) (DOE 2012). Cost prohibitive, culturally inappropriate, and short term solutions all miss the mark in comparison to developing a culture of energy efficiency.

Due to the complexity of human behavior, a missing understanding of the underlying problem of exhaustive energy use limits our ability to develop appropriate housing related energy solutions. Controllable experiments are handicapped due to a variety of variables which can cannot be fully duplicated in a lab. Technologies are used in ways designers fail to predict (Andres and Loudermilk 2011), global energy markets are volatile (Regnier 2007), and environmental beliefs sway generationally (Dunlap et al. 2000). By approaching problems with interdisciplinary teams, multi-method protocols, and an ethical stance for solving society's problems, our research team has been developing useful knowledge towards improving energy efficiency in the residential sector.

While our case study approach is not meant to be generalizable, findings from this study are very transferable (Yin 2009). Similar affordable housing units can be found nationwide and some of our findings are transferable to any building in which occupants have control over building energy systems. Our assumption that there are multiple solutions to reducing energy consumption in homes justifies the case study approach we have taken. Due to the time dependent nature of environmental systems, we believe that our actions today will shape the energy problems of the future. By developing a snapshot of the current problem, we will be able to create novel solutions and provide a philosophical foundation for the next generation of issues.

METHODOLOGY

The sample sizes for this multi-phase project varies. Normalized energy use was tracked and compared between {15+} units. Selection of each project for the energy use study included: 1) its location within the Commonwealth (Figure 2), 2) EarthCraft multifamily developments certified by Viridiant (formerly EarthCraft Virginia) and 3) those constructed and/or renovated since 2009. The energy efficiency scope for new and renovation projects follow a design and construction process that balances performance goals and prescriptive requirements in the EarthCraft program. During design and pre-construction phases, project teams engage Viridiant staff during the conceptual planning phase for energy efficiency goal integration prior to applying for LIHTCs. The typical new construction project scope includes: enclosure air-sealing and testing, space conditioning duct sealing and testing, high efficiency equipment, appliances and lighting. The renovation projects in the sample can be described as deep energy retrofits, with 30-40% energy efficiency improvement goals achieved through a typical scope including enclosure air-sealing and testing, space conditioning duct sealing and testing, high efficiency equipment, appliances and lighting. To further study variability in green building energy usage and options for influencing resident behavior through education on technologies incorporated into the energy efficient unit. The orginial study included sample units in the following formats: 1) those reporting receiving education on technologies in the unit by property managers and 2) those reporting receiving *no* education. In the latest phase of the study, a small sample has been provided another two other types of education. 1) a targeted energy education delivered by members of the research team, 2) a feedback device to instantaneously communicate energy consumption behavior.

Sample Methodology

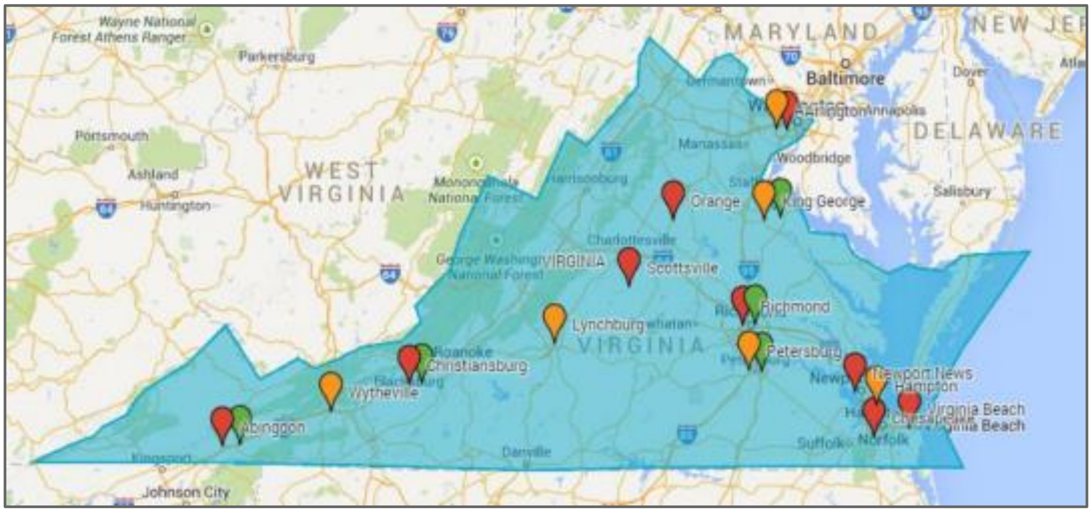


Figure 1. Energy usage study locations of sample developments and units.
Notes: red pins: Reno projects, orange pins: New Construction projects, green pins: Senior projects.

Table 1. Y_3 energy usage sample per development type, resident type and average unit size.

Division	Developments (N)	Units (N)	Residential Development Area (Avg. ft^2)	Avg. Unit Size (ft^2)
Overall	15	237	73,035	843
New	7	96	57,034	877
Renovation	8	141	73,408	816
Senior	5	89	36,405	732
Non-Senior	10	148	102,218	917

Previous work (Zhao et al. 2017) correlated the concepts of building technology, occupant behavior and energy consumption over one year from May 2013 to April 2014. The authors selected variables in computational analysis that correlated relationships among the concepts. Variables relevant to this work included: 1) observed annual energy consumption (ECo) to measure unit-level energy usage and 2) 11 variables to measure resident behaviors (for example, thermostat set points). Secondary analysis used observed energy use as the response variable (i.e., dependent variable) and the other 13 variables served as the predictor variables (i.e., independent variables) and which were distilled from the team's condensed literature review that characterized them as highly relevant to energy usage.

This work contributes to knowledge around energy consumption, capital costs and paybacks by comparing actual costs over 15 years for non-green and green multifamily projects in the Virginia LIHTC program. The work also focuses on the latent relationship between construction cost and actual energy consumption in high performance housing. Results from this study reinforce the ability to use cost data and identify critical variables for energy prediction. The work will advance the information exchange around actual costs of green buildings and the ability to capitalize on possible gains while also identifying the need to address key barriers to EE technology diffusion in the housing market.

It is important to note that the sample size changed from our previous, 1-year study to this study of energy usage in the LIHTC sample over 3 years. The sample size of the 1-year study was 207 observations and the following 3-year study contains 237 observations. Monthly energy consumption data were collected through a partnership with industry collaborators (Zhao et al. 2017). The energy use data for each residential unit were averaged from May 2013 to April 2014. The average energy use per unit was normalized by the square footage of the unit similarly to the cost data normalization.

For the sample reporting "education/training on building systems and energy," we examined three education interventions among a total sample of 230 units in the following formats: 1) residents reporting no education and 2) residents reporting education by property managers upon signing a lease or receiving educational modules when signing utility bill release forms. Determining influences on the variability of energy usage by residents will inform policies for education and incentives.

We collected the monthly energy consumption data over the past three years for a sample of 159 residential units from nine developments located in nine cities (see Table 1). These 159 units are included in our sample, as opposed to our population, as they also align with available unit-level energy data. The researchers collected monthly energy consumption through a partnership with industry collaborators (Zhao et al. 2017) and averaged from January 2013 to Jun 2016. The average energy use per unit was normalized by the square footage of the unit. 38 instances (residential units) without electricity data were removed from the initial 197.

Energy Use Normalization

Comparing the performance of developments and units is a critical component of this work. There are varying development types and sizes within the sample, so data normalization is necessary. Energy use data were normalized by dividing the annual energy use (converted from kWh/yr to kBtu/yr) by the conditioned area of each unit (square footage of the apartment) to develop an Energy Use Intensity (EUI) value per apartment per site, reflecting the energy used per square foot per year or kBtu/ft^2/yr.

The application of site EUI metrics for building performance benchmarking is similar to the mile per gallon (MPG) rating system used in the automobile industry; providing stakeholders throughout the supply chain with a standardized performance metric. Site EUI is a common normalization method utilized to compare energy use across different building types, sizes and occupant populations. Nationally, site EUI is used by government agencies including the Department of Energy and Environmental Protection Agency, industry standards organizations such as ASHRAE (American Society of Heating Refrigeration and Air-conditioning Engineers), the American Institute of Architects (AIA), the 2030 Challenge and more recently to support city benchmarking policies in New York City and Austin, Texas.

Survey Methodology

Participants of this study were surveyed via a hand-written survey at their development usually in a community room or as a part of door to door sweeps. Surveying in person requires a great deal of flexibility and effort. Property managers agreed to hold meetings of residents for collecting survey data in person or email them the link to the survey. Often residents would not show up to community meetings so provide more variability to the sample, members of the survey team went into the developments and knocked on doors, asking people randomly to answer the survey and sign releases. When on-site collection processes were ineffective, property managers were also asked to anonymously collect surveys left for residents. Property manager collected surveys are less than 10% of all surveys collected. All data collection plans were designed and approved by the researchers' Institutional Review Board (IRB) to protect the human subjects of participants. The criteria for sample selection included the building's geographical location, application of green building technologies, and sustainable construction practices.

All studies have obstacles to overcome in regards to reliability and validity. Following well documented suggestions for research design (Yin 2009) (Creswell 2013) only begins the process. Keeping the limitations and assumptions in check for a study like this is where the process becomes taxing and complex. Previous studies have shown the inability for the public to accurately perceive energy saving and consumption (Attari et al. 2010). While our energy data comes directly from the utility to ensure accuracy, other variables such as behavior, education, and thermal comfort are all subjective measures of our survey. To increase the reliability and validity of our study, the case study approach allowed us to collect details about our sample far beyond the limits of our survey. Quantitative data from design drawings and energy simulations are coupled with qualitative data from interviews with property managers, construction engineers, and designers to provide the research team with a rich understanding of the physical and social characteristics of our units of study. Assumptions such as confidential participants willingness to be honest and accurate records from utility companies are both safe in the context of this work. For reproduction of this study we strongly recommend assumptions such as the ability for visually impaired seniors to fill out a survey accurately, and the availability of a representative sample of residents to be present at community meetings be watched closely.

RESULTS

Energy Use Intensity (EUI) Over 3 Years

- Over 3 years on average, all building types in the sample are statistically correlated with reduced energy usage. Of these building types, and similar to energy usage findings, new construction has the least significant correlation, suggesting areas for future work in design and construction.
- Overall, sampled units contain an energy use intensity 20 % less than estimated.
- Sampled new construction units contain an energy use intensity 8.4 % less than estimated.
- Sampled renovated units contain an energy use intensity 26.2 % less than estimated.
- Sampled senior units contain an energy use intensity 17 % less than estimated.
- Sampled non-senior units contain an energy use intensity 21.2 % less than estimated.

Table 2. EUI Summary Table

Division	Est. EUI	Obs. EUI	Diff. EUI	*N*	Std Err	*t*	*p*	Upper 95%	Lower 95%
Overall	32.25	25.94	6.31	237	.78	8.11	<0.001**	7.84	-4.78
New	29.75	27.23	2.52	96	1.33	1.89	.031	5.17	-.13
Renovated	33.95	25.05	8.89	141	.88	10.10	<0.001**	10.63	7.15
Senior	34.28	28.42	5.86	89	1.16	5.05	<0.001*	8.16	3.55
Non-Senior	31.03	24.44	6.58	148	1.03	6.36	<0.001**	8.63	4.54

Note: Est = Estimated; Obs = Observed; Diff = Difference; Round-off errors may apply; ** = Significant at 99%.

- Across all types of residential units, the ones studied here are more efficient than the national average. Study Y_3 LIHTC units indicate an EUI average that is 55% more efficient than the National average and 43% more efficient than the Virginia average for multifamily rental housing.

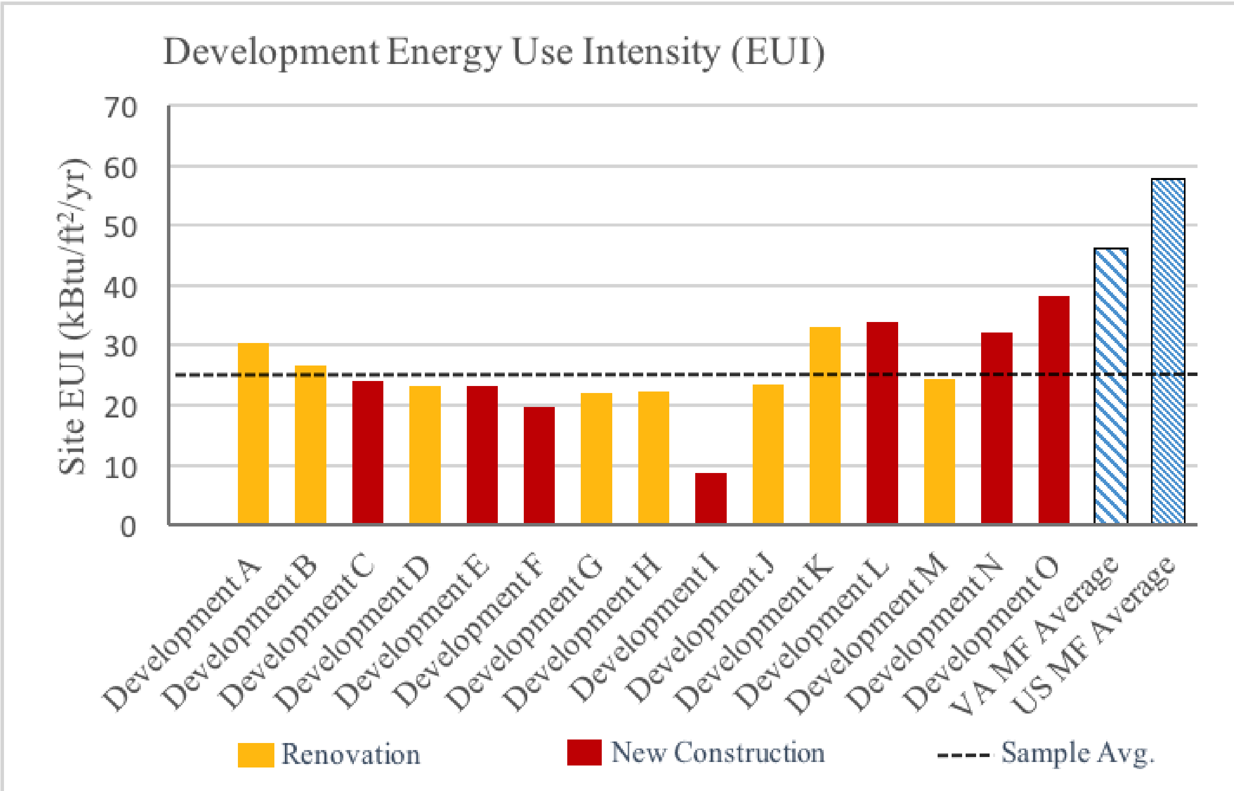


Figure 2. Development average site EUI performance from May 2013 to April 2016 by project type.

- From low-income to extremely low-income housing units, residents can save between 3.1 and 8.3 percent of total annual housing costs from energy efficiency respectively. Based on the 2015 HUD Income Limits for a 4-person family ($78,400.00) in Virginia, savings equate to 3.1% of housing costs for low-income households, savings equate to 4.9% of housing costs for very low-income households, savings equate to 8.3% of housing costs for extremely low-income households.

Table 3. Annual Energy Usage (kWh) Summary.

Division	New Standard Construction Est. Energy Use (kWh Annually)	Est. Energy Use (kWh Annually)	Obs. Use Y_1 (kWh Annually)	Avg. Obs.Use Y_3 (kWh Annually)
Overall	11,428.57 ($1,299.43)	8,000.10 ($909.61)	6,819.70 ($775.40)	6,259.20 ($711.67)
New	10,628.00 ($1,208.40)	7,439.60 ($845.88)	7,428.40 ($844.61)	6,914.40 ($786.17)
Reno	12,034.43 ($1,368.31)	8,424.10 ($957.82)	6,359.10 ($723.03)	5,799.60 ($659.41)
Senior	10,350.57 ($1,176.86)	7,245.40 ($823.80)	6,476.60 ($736.39)	6,270.00 ($712.90)
Non-Senior	12,013.00 ($1,365.88)	8,409.10 ($956.11)	7,005.60 ($796.54)	6,252.00 ($710.85)

Note: Est = Estimated; Obs = Observed

- Sampled new construction units saved 30 % or $363.79 over 1 year and saved 32.4 % or $422.23 over 3 years versus standard new construction.
- Sampled renovation units saved 47.2 % or $645.28 over 1 year and saved 51.8 % or $708.90 over 3 years versus standard new construction.
- Sampled senior units saved 37.4 % or $440.47 over 1 year and saved 39.4 % or $463.96 over 3 years versus standard new construction.
- Sampled non-senior units saved 41.7 % or $569.34 over 1 year and saved 48 % or $655.03 over 3 years versus standard new construction.

Education

- Research suggests that education on HPH technologies is an opportunity for significant energy usage and cost savings. This work continues to find a significant correlation between residents with education on EE technologies and reduced energy usage (resulting in cost savings) versus those without education.
- Residents with education had a lower average energy usage monthly and annually (over 3 years) by almost 15% (14.8%). Over 3 years, residents in units reporting “education/training on building systems and energy” contain a significantly lower monthly and annual energy usage versus those who report “no education/training on building systems and energy.”
- Residents with education had a lower energy bill by $10.56 per month. Monthly energy use for residents reporting “education/training on building systems and energy” averaged 536 kWh over 3 years and cost $60.95 per month.

- Residents without education had a higher energy bill. Based on savings for those with education, monthly energy use for residents reporting "no education/training on building systems and energy" averaged 628.9 kWh over 3 years and cost $71.51 per month.
- Residents reporting education on EE technologies saved $126.72 per year on average. Annual energy use for residents reporting "education/training on building systems and energy" averaged lower than residents reporting "no education/training on building systems and energy" by 1,113.6 kWh over 3 years and a cost of $126.72.

Table 4: Energy Use and Cost of Energy for Residents with and Without Education.

	Energy Use (kWh)	**Cost ($)***
W. Education	536.1	60.95
W/o. Education	628.9	71.51
Diff. (Monthly)	-92.8	-10.56
Diff. (Yearly)	-1,113.6	-126.72
Saving (%)	-14.8%	-14.8%

***Note**: costs calculated at price of $.1137/kWh, which was the VA state average for 2015.*

DISCUSSION & CONCLUSION

Our data show that homes can be affordable and energy efficient with the appropriate design and occupant education. Relatively small increases in efficiency can make a great impact in the lives of residents in affordable housing units. 3.1% to 8.3% of a household's annual income can be repurposed to improve a family's quality of life outside of their residential energy needs. A major finding of this study is that while newly constructed energy efficient homes performed well, renovation is shown to be an even more effective method. While new homes need to be constructed to meet the demands of an increasing population, sensibly meeting energy efficiency goals nationwide will require renovations to existing building stock.

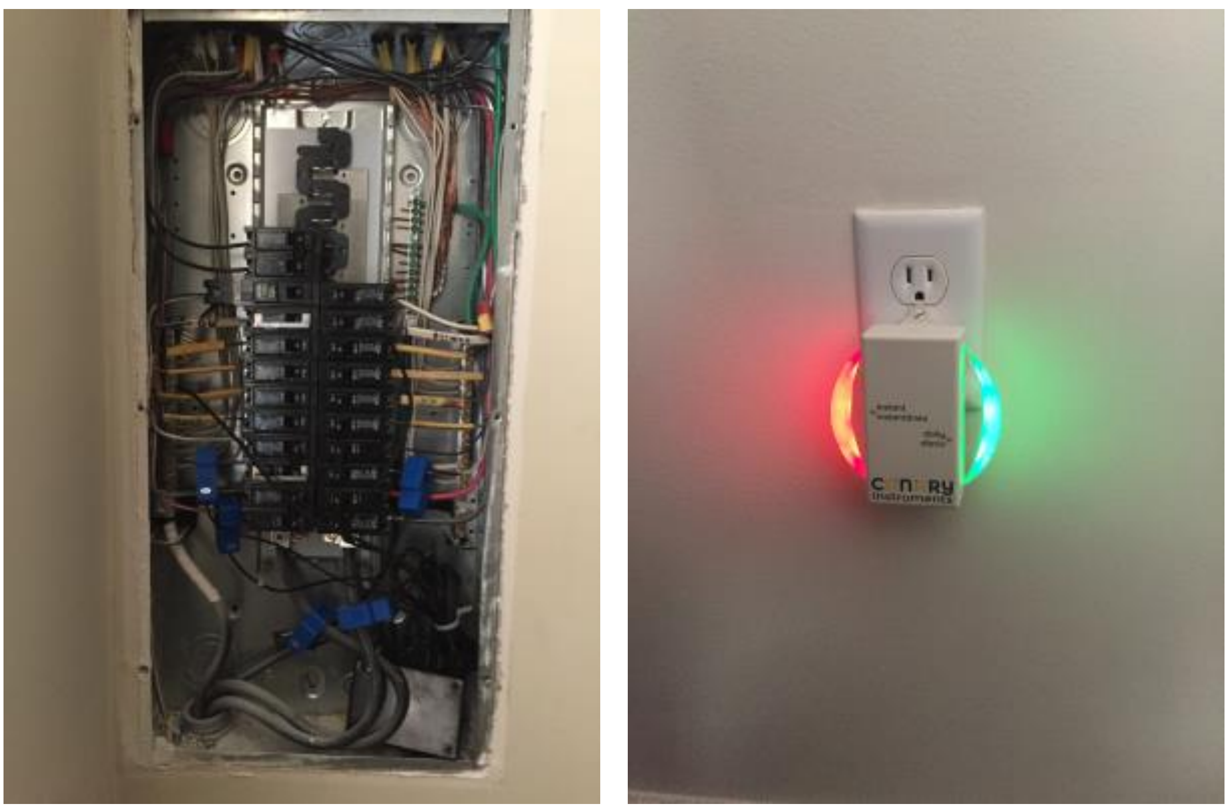
Education is a key variable in energy efficient home design (Zografakis et al. 2008) (DOE 2016) but only a limited amount of studies have been able to link behavior, education, and actual energy use in homes nevertheless affordable energy efficient homes. Previous studies debate whether education is effective or ineffective depending on demographics, home design, location, education level (Citation(Frederiks et al. 2015)). Our effort to decrease the variability through the purposeful decision to focus on affordable units with typical demographics (senior, non senior, and economic status) has allowed us to be confident in the effectiveness of education being impactful.

By providing a resident with an education on the energy systems in their home, approximately 15% savings can be returned. This aligns very closely with a previous large scale meta analysis of residential energy monitoring systems showing that homes with real time feedback with an educating effect to return 15% savings as well (Ehrhardt-Martinez et al. 2010). An education can be provided at little to no cost to a resident. While one on one training with an energy expert is expensive, at the community scale, the cost of training would be split down to a nominal cost. In many cases, energy efficiency decisions require the cost of a trained individual to make the judgement anyway. A possible solution would be to invest in the infrastructure required to improve the ability for audits and educational materials to shared in communities which commonly share the same problems and viable solutions. Not only would residents be improving their homes, they would be improving their communities with an ability to help each other with energy problems.

Many solutions are invested in that only work given the assumption of static conditions which have shown to be dynamic. Oil prices, weather, national income, all follow trends and impact the effectiveness of energy efficiency strategies. Technology solutions specifically become handicapped under conditions they were not developed for. By equipping a residence with an energy education, you can not only reduce energy use in the current situation but varying conditions as well. In some situations worsening conditions such as increased energy costs, or problematic weather can allow for education to be an even more impactful strategy. Understanding the limits of a heating and cooling system, or the energy intensity of a device can pay off big returns in moments of energy crisis. Another important aspect of education is the development of habits (Barr et al. 2005). Generally people make energy saving decisions that benefit their personal lifestyles (McMakin et al. 2002). With the proper energy education people may become energy savers who conserve energy habitually even when it provides little to no direct benefit to them. This phenomenon may explain the effectiveness of retrofits, by the way of home occupants pre-retrofit conservative energy use behaviors spillover after a retrofit. In new construction it has been shown that the perception of energy efficiency can develop poor conservation habits due to the belief that the building technologies will limit the energy consumption more than personal behavior (Andres and Loudermilk 2011).

With our statistical approach showing to be effective (Zhao et. al, 2017), expanding our case study methods to include target education, next generation energy monitors, and interviews will allow us to take a deeper look at the impact education is having on residents. There are many more variables within our data set in which we will continue to explore as our understanding of the project develops. Qualitative methods will inform us about quantitative aspects to look back at and allow us to expand our work without waiting on a larger data set. Linking the methods into a mixed-methods protocol which will provide a needed understanding of the interactions of social and technological energy efficiency innovations.

We can now look into the nuances of community level educations vs one on one, the effectiveness of online modules, and the combination of feedback and education. We are currently working on a new portion of our sample who received a target education on the community scale, and a small subset of that sample who received a next generation circuit level energy monitoring system which provides real time feedback in the form of a color scale (shown in figure 3). We will look at their data longitudinally, currently three months of data has shown a 25% reduction in the group who received a targeted education and the energy monitors have just been installed.



a) b)

Figure 3. Energy monitoring device parts a) on panel b) in outlet

Informal discussions with residents during the installation education and installation process have shown to be promising for our future interviews. Residents are curious, honest, and reflective. Residents have been clear about what they prefer in their homes, the behaviors they do not want to change (such as thermal comfort settings), and the concepts they do not know much about such as the specific energy generation or consumption of their building technologies.

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Experiential Learning Exercises to Further Understanding of Complex Building Science Principles

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ABSTRACT

In high-performing building enclosures, the reduction of heat losses can lead to higher accumulations of moisture from condensation and vapor diffusion phenomena, which in turn can lead to rot, corrosion, mold, and overall deterioration of buildings. Building construction professionals have the unique opportunity to catch design and construction errors, which if unattended will lead to costly repairs down the road. New materials, frequent change orders on site, or process changes can have a lasting and expensive impact on functionality and durability of enclosure systems. A sound understanding and proficiency in building physics and its multifaceted principles can provide students with competencies to construct and promote better performing buildings in regards to durability, efficiency, health, and comfort. Teaching efforts in this area need to move beyond traditional pedagogical practices of transferring knowledge to a more stimulating and interactive approach, where educators facilitate environments for learners to gain knowledge through interactions with building components, performing independent experiments, problem-solving, and reporting on the findings gained in the process. This paper discusses the context, design, and implementation of several building physics education lab exercises, in which interstitial and other condensation phenomena in exterior wall assemblies can be evaluated. The lab activities engage students utilizing an experimental setup of a mobile cold climate chamber, a mix of exterior wall materials, and multiple temperature and humidity sensors, to investigate the occurrence and prevention of interstitial condensation. By observing and physically touching ice that builds up within the cavity on sheathing, or fiber insulation soaked with condensate, instructors can deliver a powerful educational message even within the constraints of a classroom through this approach.

BACKGROUND AND MOTIVATION

Building enclosures date back to the first societies seeking shelter from the environment. As suitable materials were explored to provide shelter, the first construction techniques emerged. Over centuries, new materials and construction processes have evolved and sometimes been forgotten again, just to be reinvented many decades later. The history of building enclosure systems is full of anecdotes where known principles were forgotten or ignored in favor of architectural expression and exploration of new materials (Straube 2006). At times, it feels we once again forget to teach building physics principles to our A/E/C students, an observation derived from the absence of related learning objectives in accreditation requirements for university programs in the U.S. Architectural engineering has come a long way – the first architectural engineering course of study was offered at the University of Illinois (now the University of Illinois at Urbana-Champaign) back in 1890 (Uihlein 2016). Architectural engineering has since been developed as a specialization of architectural education, with some programs even offering a special focus on residential construction (Memari et al. 2014). However, teaching building science principles can be challenging and different approaches from virtual environments (Hatherly 2017; Setareh Mehdi et al. 2005) to hands-on activities (Denzer and Heimbuck 2011) have been explored to teach structural, thermal, lighting, and broader energy performance principles.

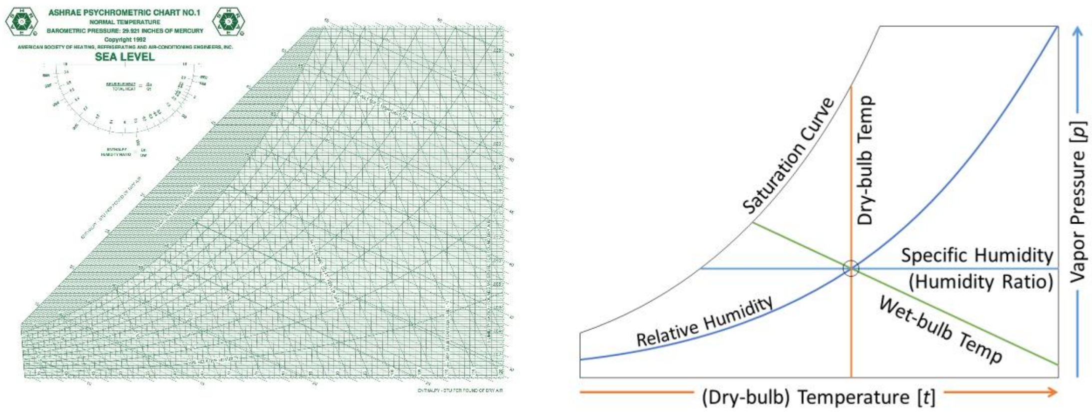
There are also efforts of broader integration of life-cycle considerations with new materials and systems and their service life performance expectations utilizing quantitative methods and test protocols incorporated into an assessment framework (Mora et al. 2011). Nevertheless, in terms of control strategies in building enclosures, the control of moisture pathways is still the most critical one when it comes to damage functions, which can range from direct water leakage to condensation and capillary movement. The result are damage states such as rot, mold, spalling, or corrosion to name only the most common manifestations. Still, this specific area of building physics or building science is significantly under-represented in curricula of higher education. The problem sets that come together in moisture control are by no means new (Rose 1997), though they require broader attention with emerging high-performance building materials and assemblies, where the reduced heat flow now deprives the enclosure system of its "self-healing" mechanism, namely the transport of interstitial moisture in form of vapor along with thermal transmission losses.

To make the complex principles of moisture migration and control more applicable, a series of experiments have been devised, which gradually bring students closer to the different problem sets that are found in building enclosures. The series sets out in exploring psychrometric properties in daily life, then moving on to understand the conditions required for the "perfect storm" observed as condensation within enclosure systems, to the ultimate frontier of building physics – the strange world of vapor pressure and diffusion through layers of different materials.

PHASE 1: EXPLORING PSYCHROMETRICS

Psychrometrics, a field that describes the physical and thermodynamic properties of gas-vapor mixtures – in the context of building enclosures, air and water vapor – can be overwhelming and confusing for those who do not have a background in mechanical engineering. It may be the multitude of properties depicted in psychrometric charts, or the sheer density of curves, lines, and different scales that makes these charts so intimidating (Figure 1a).

To break these properties into more tangible elements educators simplify the schematic diagrams, e.g. depicting only the core elements used in building physics for further discussion as shown in Figure 1b.



a) **b)**

Figure 1. Psychrometric charts (a) as published by ASHRAE and (b) schematic chart for educational reference

Among these properties, the dry-bulb (DB) temperature, which refers to the commonly measured air temperatures, are the most relatable metric and share a broad understanding of how values can be obtained. Relative humidity (RH) is also commonly used in communications such as weather forecasts. However, when pressed on how RH can be measured, most people outside the HVAC profession will draw a blank. Then again, a closer look at the psychrometric chart also reveals a second type of temperature, the so-called wet bulb (WB) temperature that intersects with DB temperatures, and probably can be obtained with a thermometer as well. However, the concept and measurement of WB temperatures is more complex. It requires a thorough understanding of the physics occurring during evaporation processes and how those relate to temperature measurements.

To provide a stimulating setting for students for exploring this relationship, an in-class experiment has been developed that engages them by applying theory to practice. This first experiment is also designed as an icebreaker to foster team thinking and exchange of ideas while observing others in the same situation.

After explaining the energy exchange between media during the endothermic process of evaporation[1], the student teams are exposed to a "MacGyver"[2] setting, where they have to quickly determine the relative humidity in the room (in which they are trapped)

[1] e.g. Michael Ermann provides an excellent illustrated version for explaining this phenomenon for architects when discussing "How Air Conditioning Works – Part 1" https://youtu.be/2wZb6HgIDE0
[2] MacGyver is an action-adventure series that ran in the U.S. and abroad in the later eighties. MacGyver employs his resourcefulness and his knowledge of chemistry, physics, and technology to create inventions from simple items solving problems in situations that are often life-or-death crises. https://en.wikipedia.org/wiki/MacGyver

in order to safely disarm a bomb that otherwise could go off. As typical for the MacGyver series, there are always a set of items "conveniently" found nearby to solve the problem.

Materials, Equipment, and Preparation

Each student team (teams of 3-5 work best) is provided with the following items that they "found" in the space: a semi-broken thermometer; a few rubber bands; a piece of string; some gauze pads from an emergency kit; and a paper clip[3] (Figure 2)

Figure 2. Items to be provided for "MacGyver" experiments

The thermometers can be purchased from your local hardware store and have no need to be highly accurate as they will be only used for comparative temperature measurements, where they should function accurately enough. A couple of rubber bands are sufficient, but a few extra may not hurt in case a band rips or gets lost in the process. In terms of string, 2-3 feet is enough and can be pre-cut for the students to use without the need for handing out knifes or scissors. Gauze pads can be purchased in bulk at local pharmacies, and 3-4 pads are sufficient for each team to have.

Experiment Setup

The setup for these experiments is minimal once the items are purchased, prepared, and sorted for each team. It has been proven helpful to collect and hold the items in transparent zip-lock bags for distribution. The students should also have been provided with a printed psychrometric chart during previous class times, which they can conveniently consult during the experiment (MacGyver would find an old copy inside the cover of the air handler).

As the instructor and supervisor conducting the experiments in a competition format, a digital thermometer/hygrometer (Figure 3a) should be at hand to judge the different teams in terms of who came a) closest, or b) fastest, or c) most creatively to their final solution. Furthermore, rather than having students resort to using just any liquids they have around, it is helpful to have a bottle of water readily available for students seeking to wick their pads. This water should be as close as possible to room temperature as it otherwise distorts and/or prolongs the process of obtaining useful results.

[3] the paper clip is useless in this scenario and just added as a distraction – but there just has to be a paper clip somewhere in McGyver episodes.

Most of the commonly available exterior thermometers have a less exposed liquid bulb, which can make the assembly of a wet bulb thermometer more challenging and less effective. By breaking off the bottom area of the plastic holder (a set of pliers can make this a more controlled endeavor), the bulb can be exposed and will be thus directly accessible for the wet gauze pads and rubber bands (Figure 3b.)

a) **b)**

Figure 3. a) digital thermometer and hygrometer for use by supervisor; b) half-broken analog thermometer handed out to student teams

Experiment Execution and Discussion

While the students have to identify the purpose of each item by themselves, it helps if they observe other teams in their pursuit. There is usually one team charging ahead, either with a student on board knowing about wet bulb thermometers, or just being creative with evaporation and connecting string and thermometer. To challenge critical thinking, the teams should not be allowed to access the internet during the experiment.

Once a team starts swinging their wet bulb thermometer above their heads, others observe that and usually quickly try to copy the effort (Figure 4). However, there are always some teams missing the wetting part assuming that the cooling effect comes from the convective heat exchange as a result from the movement in air. This, in turn, is a great learning experience, which allows for directly observing and comparing the cooling effect of the evaporation process to standard room temperatures.

Figure 4. Student teams explore their MacGyver-skills to assess RH in the space

There is one more challenge involved that was even observed when this exercise was carried out in a workshop with experienced educators and professionals. Obviously, educators quickly knew how to assemble and use a wet-bulb thermometer. However, in their enthusiasm to be the first to report results they overlook that there is only one thermometer at hand. To obtain relative humidity, they would need two temperatures – the dry-bulb temperature of the room, and the then acquired wet-bulb temperature. Teams that did not take note of the original (dry-bulb) temperature reading of the thermometer had to go back and dry their device to quickly get it back to room temperature in order to lookup the respective RH in the psychrometric chart.

PHASE 2: EXPLORING THE DEW-POINT

With a deeper understanding of relative humidity, wet-bulb temperatures, and effects of evaporation students can then be guided to explore the "limits" of the psychrometric chart – the saturation curve, more commonly known as condensation. While condensation is frequently observed in daily life, such as when forming on a window during colder seasons, or on the outside of a glass of ice-cold beverage, the direct relationship of the required ingredients is initially not that obvious to students.

To better understand the environmental conditions that lead to condensation of water vapor in the air on different surfaces and to relate observations back to the psychrometric chart, the following team-assignment has been developed. Theoretically, the set of experiments that are part of this assignment could be mostly carried out as an in-class experience. However, the exercises provide more opportunities for exploration as a team homework assignment.

As a team, they will have to determine the psychrometric characteristics of different air and moisture conditions by investigating the occurrence of surface condensation on different containers carrying water with different temperatures (Figure 5). Using a variety of provided digital thermometers and hygrometers, they have to investigate surface condensation risk for different air-moisture conditions, observe results for different surface temperatures, and document their observations supported by graphical representations in the psychrometric chart.

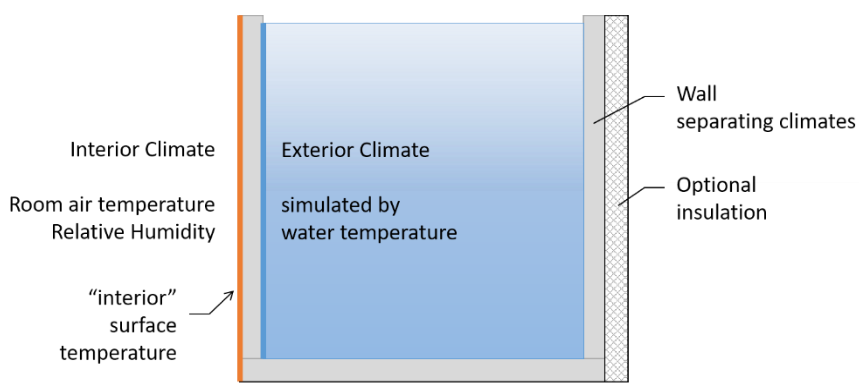


Figure 5. Container setup to create different "interior" surface temperatures

Materials, Equipment, and Preparation

The student teams are each provided with a set of tools that allows for various temperature and humidity assessment techniques: a contactless infrared (IR) thermometer gun, a submersible aquarium thermometer, and a digital weather station with a display for room temperature and relative humidity (Figure 6)

IR thermometers for this purpose can be purchased cheaply online, and are only used to determine surface temperatures of the utilized containers. If a variety of materials will be explored, an IR thermometer that allows for correction of emissivity is preferable. The required digital aquarium thermometer can be obtained from a local pet store, or also be ordered online for less than the price of a coffee drink. The thermometer should be water submersible to allow for temperature control of the "exterior" climate, which is replicated by the water temperature within a container. The digital room thermometer and hygrometer is used to assess the current interior air condition as a starting point for any interior surface condensation analysis. Overall, the total set of tools provided for each team could be obtained for $30 or less.

Figure 6. Items to be provided for dew-point experiments

Experimental Setup

The experimental setup should replicate assessing indoor air conditions against condensation risk triggered by different surface temperatures that are caused by exterior climate conditions.

The student teams have to investigate a mix of the different scenarios and air conditions. Specifically, they are encouraged to explore:

- Different air temperature conditions (e.g. room temperature vs. basement or refrigerator conditions)
- Different relative humidity levels (e.g. normal room humidity vs. a bathroom after the shower has been run for several minutes)
- Different thermal performances of the climate separating walls (e.g. glass container vs. Styrofoam cups or containers with a sponge sleeve)

Students are asked to create climate conditions with different containers (enclosure systems), different water temperatures (exterior climates), and different indoor air conditions. For each air condition, they are asked to record the indoor air temperature, the relative humidity of the air, the container surface temperature, and the "exterior temperature", i.e. water temperature. They then need to assess and record from a psychrometric chart or online tool the applicable dew point temperature and compare against their observations. They are encouraged to investigate different surface temperatures by changing the water temperature. E.g., starting with water at room temperature and gradually adding ice cubes to the water, which in turn will lower the surface temperature of the container. Once different "exterior" (water) temperatures were explored, they have to repeat the test with containers of different "wall" materials. For example, compare two containers with the same temperature of water, but different conductivity of material – one comparison could be a glass bottle or soda can with and without foam sleeve (Figure 7).

Experiment Execution and Discussion

When students conduct these experiments in class, instructor intervention typically prevents making major mistakes and at the same time improves the quality of results. However, conducting the experiments in their own residential settings can increase the learning outcome, if they decide to invest the time investigating in-conclusive observations. While graduate students usually are inquisitive enough to engage in this discourse, the reports generated from undergraduate teams typically show mixed results with several unaddressed mistakes made in the field. Discussing these mistakes through an in-class review can help in terms of how to detect and correct errors in their future careers.

a) b)

Figure 7. Assessment of surface condensation risk based on a) different "exterior" temperatures and b) different "wall" materials

Observed issues in different report submissions range from measuring errors to an incorrect understanding of observed principles. A frequent measuring error occurring when students utilize an IR thermometer is that they trust the laser pointer as the point of reference for temperature readings ignoring the optical cone that is formed by the lens, which drastically increases the area of measurement with increased distance to the object. Temperature readings then become a reflection of broader surface temperatures emitted by the environment rather than the location they were supposed to record. A second common error with IR thermometers is not understanding the underlying measurement principle and pointing it at reflective surfaces (e.g. glass bottles or aluminum cans). The typical emissivity of surfaces is expected to be between 90-95% for standard readings, so measuring surfaces with an emissivity of 10% are much more impacted by the surface temperatures of objects reflected by those. A quick fix for these situations could be applying a matt-finish tape on the surface before taking readings.

Incorrect assessment of dew-point temperatures from psychrometric charts is another place for errors. Students may follow the lines of wet-bulb temperatures as the "shortest" way to the saturation line and in turn do not find accordance between practice (experiment) and theory (psychrometric chart), as they overestimate the actual condensation risk. Other errors show how hard it is for students to comprehend the replicated principle, as they attempt to record surface temperatures inside the container pointing at the interior rim above the water surface or the water surface itself rather than the exterior container surface. Some students also ignore sequencing of the experiments by moving the container quickly in and out of a refrigerator or a humid bathroom and then observing transient short-term effects that do not match the steady state assumptions set forth for simple conductive temperature problems. The most critical errors observed were those where students reported inconsistencies that were ignored and/or not addressed, such as recording lower surface temperatures on the container than the actual water temperature or calculating dew-point temperatures significantly above room temperature without observing fog or rain in the same.

Overall, these experiments can contribute to a hands-on understanding of what happens when humidity laden air enters cavities of building enclosures and hits colder surfaces, be it the warmer interior air hitting the cold OSB sheathing during winter periods, or hot humid exterior air finding its way to the cooler interior gypsum layer in air-conditioned homes during summer times.

PHASE 3: EXPLORING THE INTERSTITIAL SPACE – VAPOR DIFFUSION

One of the most complicated concepts to comprehend in building physics is the principle of vapor diffusion. Diffusion not only happens through fibrous materials but also through otherwise "solid" materials, such as wood fiber or gypsum boards. While less critical in terms of quantity compared to condensate amounts from infiltration, diffusion can become a critical process that requires evaluation in terms of condensation risk and long-term damage potential, specifically in high-performing enclosures. The limited heat transfer in highly insulated wall systems, paired with a sharper drop of temperatures across these insulation layers can lead to interstitial condensation where vapor moves unrestricted while dew point temperatures quickly drop.

The relationship between thermal conductivity and vapor permeability is one of the most complex principles to understand, explore, and ultimately apply in practice. To provide a tangible context for this phenomenon, a third in-class (or lab) experiment has been designed to make the involved processes approachable.

The experiment is comprised of a chest freezer that is utilized to create a cold exterior (winter) climate. Different wall assemblies can be tested against this climate based on the current interior climate available in a space (Figure 8). The freezer lid is replaced by an insulation panel with an opening frame to receive different specimen holders. Specimen can be prepared in advance and quickly changed out with the various test assemblies from different teams.

Figure 8. Chest freezer reconfigured as a mobile environmental climate chamber

Materials, Equipment, and Preparation

The chest freezer can be an off-the-shelf appliance, which can be found in any of the common household stores. There are no specific requirements other than it should have a thermostat (which almost all do) for an opportunity to test against different "exterior" climates. Thermostats typically allow temperature settings between 30°F and -10°F. A 5-ft^3 volume freezer works perfectly well for the setup; a 7-ft^3 does not provide any significant advantage. While an even larger freezer may allow side-by-side comparisons when equipped with two openings, it may also lose its mobility to be move in and out of a classroom.

For the top-panel and specimen holders standard 2" XPS boards can be utilized, which are easy to cut with a table saw. A hot wire cutter is not necessary for preparing the XPS frames. The foam board can be glued with XPS compatible adhesives; it is recommended to check manufacturer requirements to achieve long-lasting, sturdy frames. To seal the joints between top panel and rim of the freezer, as well as the gap between specimen holder and top panel a roll of vapor-tight rubber foam weather-strip is required (Figure 9).

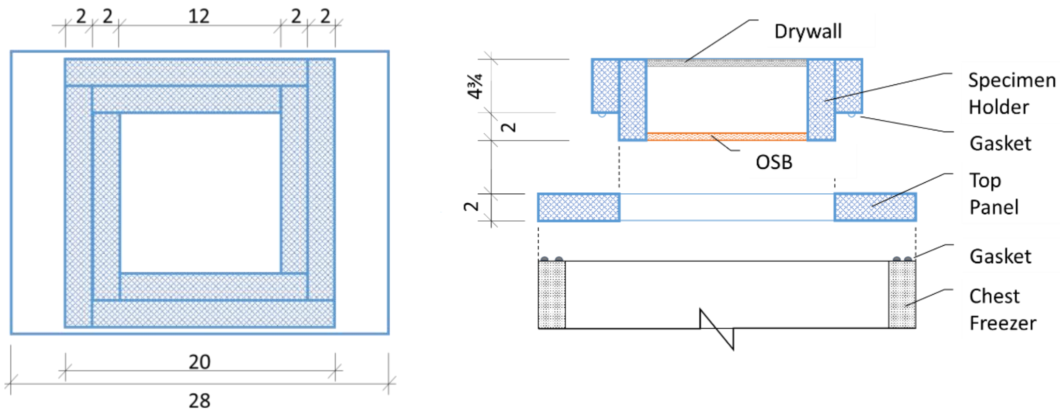


Figure 9. Top panel and specimen holder made of 2" XPS

The instrumentation for this experiment is accomplished with an Onset HOBO-ZW wireless node system, which allows for flexibility when moving the freezer into different locations. For this setup, a receiver node (ZW-RCVR) and preferably two 4-channel data nodes (ZW-005) are required. The ZW-005 already comes with a combined temperature and RH sensor and allows for the addition of two more analog sensors.

To obtain a full temperature profile across the entire assembly these other ports can be equipped with standard temperature probes (e.g. TMC6-HE). If more data points are to be collected, the system can be easily expanded by another 4-channel node. The data logging is actually done through a remotely connected computer that fetches the individual records from the different nodes through a USB connected receiver.

a) **b)** **c)**

Figure 10. a) HOBO ZW wireless node, b) air/water/soil temperature sensor, and c) HOBO ZW wireless receiver

While the setup discussed here is more expensive than the items utilized in the previous experiments, the equipment for the entire configuration can be purchased for less than $1,000 and could be financed at an institutional level, through an industry sponsor, or a fund-raiser organized by student chapters.

Experiment Setup

The top panel is cut from an XPS board and rests on foam weather strips that seal the freezer cavity against room air conditions. The specimen holders are also built out of strips cut from 2” XPS boards and glued together to hold a 1’x1’ wall assembly of up to 6.75” thickness (2x6 wall insulation cavity with ¾-in OSB and ½-in drywall) in this setup. Since the individual layers of the wall assembly are put in place horizontally and not vertically, as they would be in a wall, an edge trim element is mounted to the bottom to prevent the exterior sheathing from falling due to gravity. Furthermore, some small distance holders (e.g. balsa wood sticks) need to be placed in the corners to prevent compression of fibrous insulation materials when the heavier gypsum layer is placed on top of the assembly.

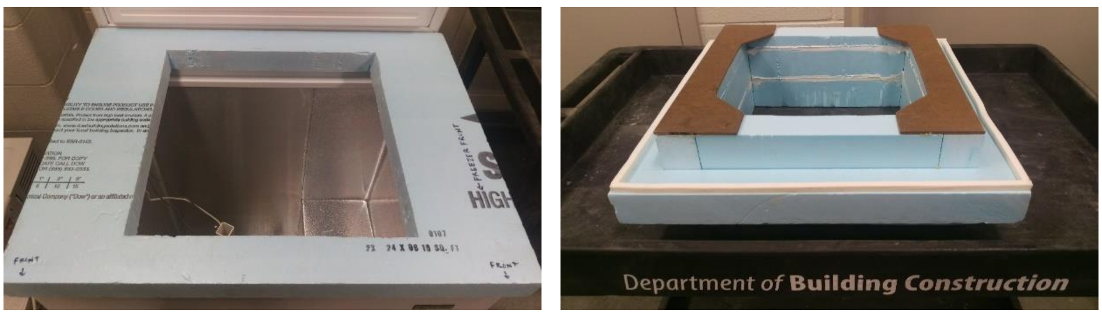


Figure 11. Top frame and specimen holder made of 2” XPS

It is helpful to have pre-cut (12”x12”) wall assembly materials such as OSB and gypsum boards at hand, as well as a variety of insulation materials (e.g. cellulose or faced fiberglass batts) to quickly facilitate the installation of wall assemblies in the prepared specimen holder. To allow for reusability of the specimen holders the use of removable sealants, such as TAP’s *SEAL 'N PEEL* or Red Devil’s *Zip-A-Way* sealants, is recommended.

Experiment Execution and Discussion

The experimental setup can even be finished during a class session, where students come up front to assemble and install their wall specimens. The setup in class also teaches students how to place and deploy a data-logging system. Students can be introduced to different sensor types and their installation requirements to capture various properties correctly. For example, the air/water/soil temperature sensors utilized in here have the tendency to be impacted by their radiant exposure when exposed to air. Thus to record surface temperatures correctly they must have a secure conductive contact with the respective surface and occasionally may require shielding from objects with higher temperature difference (e.g. radiant heat sources) in their surroundings.

An actual test cycle takes several hours to establish steady state conditions and thus exceeds a normal class period. However, initial results of an increase in relative humidity in the cavity can be typically observed within a couple of hours.

Figure 12. Installation of a sensor a) within freezer b) on the exterior OSB board and c) closing of the cellulose filled cavity with a gypsum board

Figure 13. Air sealing of the cavity with removable sealant on the exterior side and taping of the drywall joints on the interior side

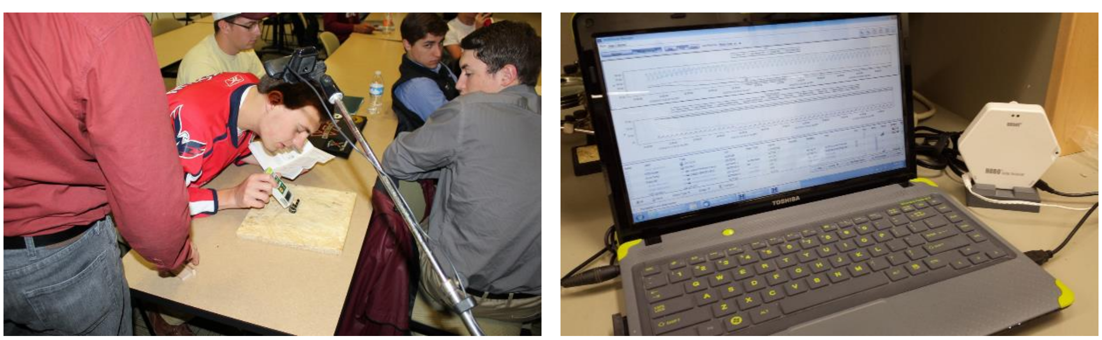


Figure 14. Measurement of initial moisture content of OSB board; and data-logging and monitoring station with wireless receiver

It is recommended to have a test run over several days. This demonstrates that while steady-state temperature conditions are typically achieved within 3-5 hours, there often is a constant increase of moisture accumulation within the cavity that eventually can trigger interstitial condensation build-up and consequently lead to rot and mold invisible from either side of the wall.

a)
b)
c)

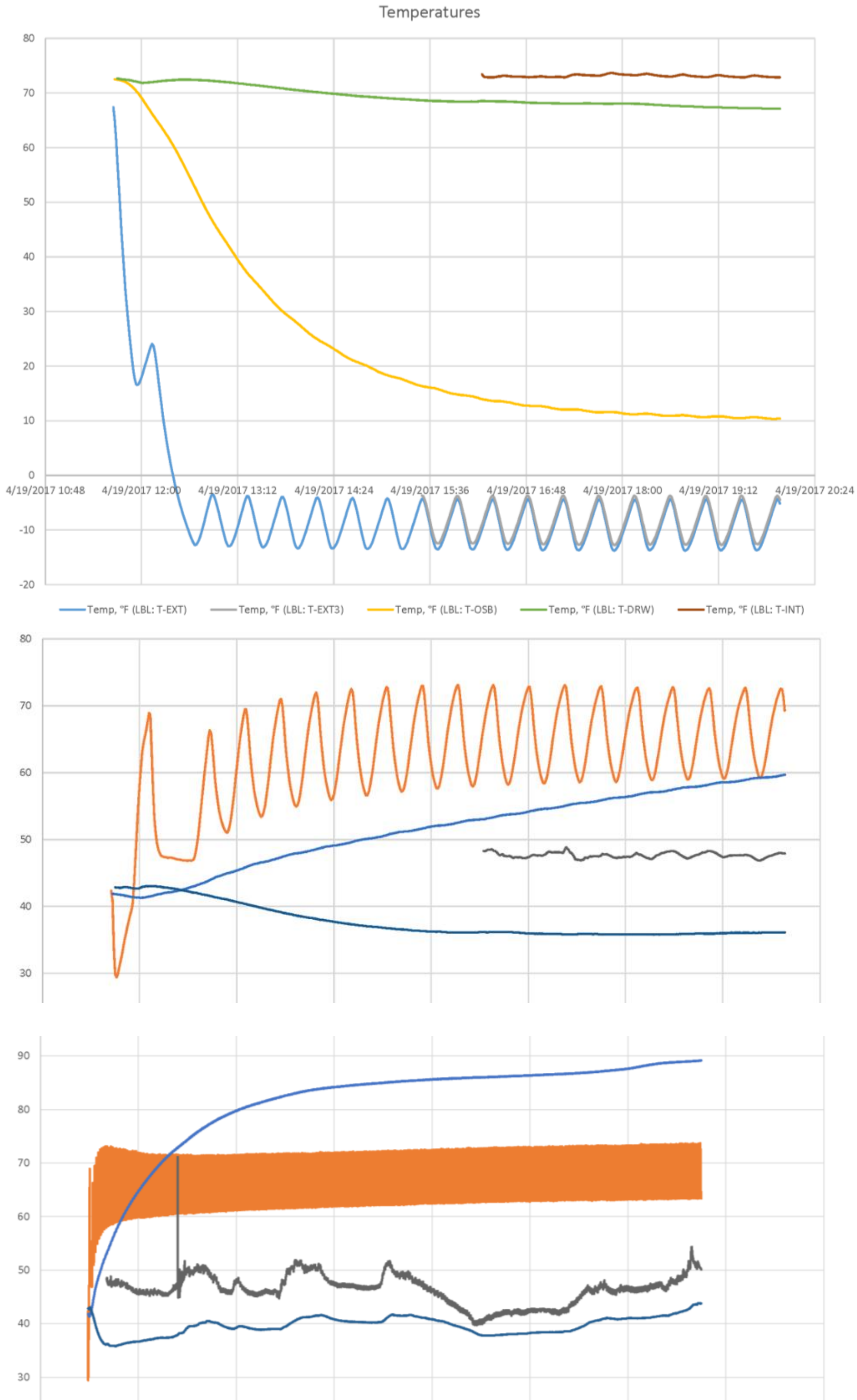


Figure 15. a) Temperature measurements over hours
b) relative humidity measurements over hours and c) over days

CONCLUSION - ACHIEVEMENT OF LEARNING OBJECTIVES

The experiment series presented in here slowly introduces the student in an engaging and explorative way to psychrometric concepts of air movement and moisture control issues in building enclosures. While the first in-class experiment is mostly designed to gain some familiarity with the various properties of psychrometrics, it also teaches the challenges of actually obtaining real measurements in a qualitative relevant way. It is highly likely that no team will come close to the actual relative humidity in the space, which in turn becomes a lesson learned in measurement accuracy and trust related to the evaluation of obtained results. The second experiment series challenges students to link real-world observations with theoretical knowledge. However, the abstraction of recreating environmental boundary conditions by utilizing a different medium than air does not work with all students equally well. It requires them to think outside the box to connect the scenario with conditions that can occur through infiltration of gaps in exterior walls, and the condensation risk that such air movements represent.

Figure 16. Insulation frozen to the OSB and build-up of ice from interstitial condensation

The final experiment, while studying the most complex physical relationships of the series, delivers the most unsettling response. When students participate in opening the wall, and encounter the insulation material frozen to the OSB or touch actual ice-buildup on the exterior side of the cavity, this provides a lasting learning experience. It is the hope of the authors, who are also instructors of a building physics course, that this impression lasts for a lifetime, so that when our graduates are out in the field and are confronted with new material combinations and different environmental conditions, that they are aware of the many factors that contribute to a well-managed and constructed high-performance enclosure system.

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Implementation of Project Based Learning in a Building Science Curriculum

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ABSTRACT

Project based learning (PBL) fully engages students in the subject area, promotes team work, transdisciplinary collaboration, allows student teams to engage and solve community design challenges and can ultimately lead to broader student worldviews. PBL, however, comes with challenges including project definition and meaningful student assessment.

The authors began the process of exploring PBL through a National Science Foundation Transformation Undergraduate Education in Science, Technology, Engineering and Mathematics (TUES) award. The program was piloted for two semesters under the TUES award and is now in its fifth semester operating as a special curricular track in parallel with the existing, traditional curricular track providing a total of 3+ years of PBL experience. The authors are currently reworking the existing program curriculum to fully integrate an PBL capstone in the senior year while maintaining a clear curricular path, creating a sound base of projects and maintaining resource limits (including space, materials, and personnel).

In this paper, the authors discuss their successes and challenges in implementing PBL in an undergraduate Building Science program. Specific topics include the obstacles and challenges met during more than 7 years of both spontaneous and planned project based PBL experience.

REVIEW OF PROJECT BASED LEARNING

Project based learning or PBL is a term commonly used to describe an active learning pedagogical “style” and can be roughly associated with other active learning terms including discovery learning, problem based learning, experiential learning, and inquiry based learning. These active learning approaches trace their roots to constructivist learning theory as established by John Dewey and continued by educators including Maria Montessori and Jean Piaget (Dewey, 1974; Ültanır, 2012). The PBL method moved from its elementary education roots into higher education first in medical schools during the early 1970’s and more recently in engineering schools in the form of capstone design courses (Barrows, 1986; Dutson et al, 1997).

Project based learning is a student-centered method of teaching that intends to engage students in the solution of an authentic problem (Blumenfeld et al, 1991). Proponents of PBL contend that the method enhances student learning outcomes because students are more motivated to engage and learn the material if they engage in solving an authentic problem; students participating in PBL are more likely to retain and internalize knowledge; and PBL allows students to relate their theoretical knowledge to the real world in essence allowing them to synthesize a unified view of their field of study from the fragmented content gained through various and disparate lectures and courses (Blumenfeld et al, 1991; Tasci, 2015; Wu and Hyatt, 2016). Opponents of project based learning (and similar active learning techniques) object to the teaching method primarily because it requires that the teacher not give students a solution but rather coach them towards answers or solutions that the students must develop on their own-- opponents refer to this aspect as minimal guidance during instruction (Kirschner et al, 2006).

PBL AT APPALACHIAN STATE UNIVERSITY

The Building Science program at Appalachian State has developed a unique curriculum of educational “product offerings” housed within the Department of Sustainable Technology and the Built Environment. By crafting a synthetic baccalaureate degree program - a common core of courses with three concentration areas in Architectural Technology and Design, Construction Management, and Sustainable Building Systems - Building Science at Appalachian State presents a “liberal arts method” to immerse students in the building industry as a whole. Crossover courses in Appalachian’s Sustainable Technology program offer students opportunities to integrate energy-related issues into their education. The flexibility inherent in this curriculum structure emerged due in large part to a desire among both faculty and students for project-based learning activities.

Architectural Design Studios: A First Step in PBL

In the fall semester of 2006, a new concentration in Architectural Technology and Design was established within the undergraduate Building Science program at Appalachian State University to complement the pre-existing concentration in Construction Management. Not only was there student demand for a formal architectural emphasis of study, but a desire for more courses devoted to project-based learning. Up to this time, the program had historically included two design courses, one residential and one commercial, in an effort to strengthen communication amongst construction industry professionals and provide opportunities for creative problem solving for future construction managers. Because these courses proved to be the most popular in the program -- which can be attributed to their focus on project-based learning -- the faculty decided to expand course offerings with PBL emphasis into the new concentration and more design studios.

Over the last eleven years, the four architectural design studios -- one each semester for the final two years of study -- have engaged in a plethora of project-based learning exercises. From small one-room dwellings to massive campus planning endeavors, PBL has launched a new wave of creative inquiry and tangible expression of ideas for students in the undergraduate Building Science program.

Many of the projects within the architectural studios have been for external clients rather than purely hypothetical in nature. To engage students in service learning as well as promote a more real-world experience, professors used these projects to equip students for future employment. Although these design-only projects did not include cost estimates and construction documents, the process of experiencing a real-world project captured the students' attention and helped "connect the dots" between many of the disparate elements of their coursework. As of the spring semester of 2017, students in these architectural design studios have completed more than ten design-only service learning projects with non-profit or governmental clients.

Design/Build: The Next Step in the PBL Experience

With the growing success of the Architectural Technology and Design concentration and the numerous design-only service learning projects completed, the faculty ventured into a more complex form of PBL: design/build. In the fall semester of 2009, an architectural professor and sixteen senior design students inaugurated the design/build trajectory of Appalachian State. Within a single semester, the students worked with a non-profit organization to design and build a solar-powered mobile performance stage used to host concert events at a local park.

Although there were many challenges with this new form of PBL, the student learning that resulted from the experience encouraged the Building Science faculty to continue with design/build projects as a part of the student experience. Up to this point, however, design/build and much of the real-world projects had been limited to the Architectural Technology and Design studios. Many engineering-based and construction management faculty became optimistic about these PBL experiences, especially design/build. The hope was for all students in Building Science -- both architectural and construction management -- to have this unique experience before graduation.

Solar Decathlon: PBL, Interdisciplinarity, and Competition

The opportunity to have a more integrative experience amongst Building Science students as well as other programs in the College of Fine and Applied Arts, such as Sustainable Technology, Interior Design, and Industrial Design, became a reality with Appalachian State's acceptance as one of twenty teams selected for participation in the 2011 Department of Energy Solar Decathlon Competition (see Figure 1). The two-year design-build residential project was led by three Building Science faculty and a core group of twenty undergraduate and graduate students. Over two hundred students from across the university participated in the project in some capacity as did multiple consulting professors. By the fall semester of 2011, the ASU team had designed, built, tested, disassembled, transported, and reassembled its project, known as the Solar Homestead, onto the National Mall in Washington, DC for the Solar Decathlon competition. The interdisciplinary team won the coveted People's Choice Award as well as finished first place in the Solar Hot Water competition, Second Place in the Communications competition, and third place in both the Architecture competition and Home Entertainment competition.

Figure 1. Appalachian State University's Entry into the U.S. Department of Energy's 2011 Solar Decathlon, The Solar Homestead.

Building upon the success and momentum of the first Solar Decathlon project, ASU competed again. This time the university's entry was in the 2014 Solar Decathlon Europe competition (see Figure 2), requiring the design/build project to deal with the complexity of international standards and cross-Atlantic travel. Another interdisciplinary team was established, comprised of a core team of Building Science students as well as students from other departments and in the College of Fine and Applied Arts. The two-year project was another success for the university garnering first place in the Energy Balance competition and ninth place overall out of the twenty finalists.

Figure 2. Appalachian State University's Entry into the 2014 Solar Decathlon Europe, Maison Reciprocity.

While these competitions provided significant student learning and real-world experience, they were considered special projects and produced minimal student credit hours. The credit hours that were achieved by students were often electives and not an essential part of an undergraduate program of study. Considering the substantial time investment and overall commitment required, it seemed as if these projects demanded too much from undergraduate students while not helping make their path to graduation reasonable.

The Solar Decathlon projects also possessed other difficulties. They were very expensive endeavors, requiring substantial financial, faculty, and administrative efforts. Although the Department of Energy provided some grant funds to help begin the projects, significant fundraising was required to execute these projects to their full extent. While these projects brought international accolades to the Building Science program and the university at large, their impact to the institution's context - rural Appalachia - was minimal. The program had historically gravitated to projects and research that helped local communities, such as some of their earlier design/build endeavors; however, the Solar Decathlon projects did not become permanent artifacts of the region after the competitions nor of the campus itself.

IDEXlab: Integrating PBL, Curriculum, and Disciplines

In an effort to make PBL -- specifically design/build -- a more integral part of students' academic experience, the Building Science faculty sought to develop a program that intertwined into the existing programs of study. Supported by funding through a National Science Foundation (NSF) Transforming Undergraduate Education in STEM (TUES) grant, a new pilot program called IDEXlab was created to mitigate the inherent curricular issues of past PBL efforts and develop a more interdisciplinary approach. Beginning in the summer of 2013, the faculty research team spent a year investigating comparable programs and planning the pilot curriculum. In the fall semester of 2014 and the spring semester of 2016, the IDEXlab (v1) pilot curriculum was executed as an alternative senior-year experience for 16 students - 8 from the Architectural Technology & Design concentration and 8 from the Construction Management concentration. Each student replaced their senior level coursework within the major for a total of 18-20 credit hours.

Within the year-long experience, students were divided into a variety of interdisciplinary teams for the multiple projects within the curriculum. The first project was a ten-day design build for electric composting toilet structures located on a farm used by the university's agricultural program. Although the two teams missed their deadlines and the final products were of mediocre quality, two buildings were designed and built with students learning many valuable lessons about budgets, time management, and team dynamics. Some shorter one-day charrettes were woven into the experience just before and during the process of the student teams' major projects. One eight-person team was charged to design and build a 20-stall farmer's market in a nearby town while the other eight-person team was assigned a small visitor's center complex in a local park. Both projects were completed by the student teams with one on time and on budget, and the other months late and well over budget.

Figure 3. (left) Porch entry of IDEXlab's (v1) Valle Crucis Welcome Center. (right) Construction of IDEXlab's Alleghany County Farmer's Market.

With the student learning success assessed during the pilot study, as well as the impact the projects provided to local needs, IDEXlab was continued for second year (v2). Because of the fatigue experienced by the ambitious efforts of the pilot - by faculty, students, and donors - the second year of IDEXlab concentrated on developing an internal research project, the MOBILab.

The MOBILab (see Figure 4), is an energy self-sustaining mobile classroom and research station that was created to meet the demand for classroom spaces at the Department's various remote research facilities. The MOBILab was designed and built for the Department of Sustainable Technology and the Built Environment. While not an external client, this project still shared the goal of connecting students with the community and the opportunity for a mobile shared resource. The MOBILab cohort was comprised of 16 students equally selected from the three concentrations (Construction Management, Sustainable Building Systems, and Architectural Technology and Design). Although the scale of the project was small in comparison to past projects, other unavoidable factors made the project complex and prolonged.

If it were not for the setbacks, a project similar in scope and scale, could prove to be an appropriate choice for future IDEXlab projects. Because of the scale of the project, it is a much more sustainable project for both students and faculty. Even with a smaller cohort, this project is more appropriately scaled for a year long program. And while the size restrictions for mobile structures is limiting, it provides clear constraints and boundaries for the students, letting them focus on a concentrated design problem. Additionally, the project allows students to consider design and detailing for all the major components of residential construction. The MOBILab is a prototype which will be modeled for further uses in the IDEXlab projects to come.

Figure 4. IDEXlab's (v2) MOBILab in use at the Sustainable Technology and the Built Environment's Small Wind and Research Demonstration Site on Beech Mountain.

IDEXlab v3 took on an atypical project type, HOW Space, a creative and collaborative gallery space. The College of Fine and Applied Arts HOW space was a major upfit to an existing building in downtown Boone, NC. The intent of the space is to connect students and the community through showcasing creative work and hosting college and community events.

The project was heavily interiors focused and even more millwork focused, giving the students a limited variety in curriculum content. However, HOW space did provide students valuable and relevant experience undergoing the permitting process and getting more acquainted to interpreting code. While this project was an unclear line between internal and external projects, we found the goal to be "a catalyst to the community" relevant in meeting our criteria for project selection. Another study notes that if projects are meaningful to students (e.g. community based) students engaged more fully in the project (Lee et al, 2014).

Currently, IDEXlab v4, is working on two projects for the academic year. The first, is building the docking station for the completed MOBILab, the mobiLANDING (the foundation for this project can be seen in the right image in Figure 4). This project has been designed by a previous group of IDEXlab graduate students. This year's cohort is responsible for using the plans to prefabricate the truss and deck sections and then erect the structure on site.

Concurrently, the cohort will be developing a schematic design master plan for the City of Elizabethton Tennessee's downtown Historic Covered Bridge Park and Edward's Island Park. While the nature of this project is heavily design concentrated, it allows students to explore and research the many layers and complexities of a community based project. The students are enthusiastic to work on a community driven project as they know they can make a significant impact. And although there is no directly related build component to the

Elizabethton project, the mobiLANDING project provides the tangible experience to the curriculum.

BENEFITS AND WEAKNESSES OF PBL

Strengths and Opportunities of PBL as it relates specifically to BS education

Each of these unique project endeavors extracted similar positive and negative outcomes as they relate to the Building Science curriculum objectives. The most valuable points are identified here, as either a strength or an opportunity. These strengths and opportunities have been determined based on qualitative evaluation of the following metrics; the authors' observations over the course of 3 years of PBL implementation, student feedback through course evaluations and individual student reviews at multiple intervals throughout the academic year, and industry professional's feedback after working with PBL student alumni.

Strengths

When students learn of the opportunity to work on a PBL project in lieu of traditional course equivalents, we typically find that those that would be interested in the program, are eager to work. Part of this eagerness (based on student feedback), is due to the mentality of "getting out of the classroom" or "having more freedom to work independently". Another critical factor to attract students is the opportunity to work on real projects and for real clients, this has an additional factor, see the next section on *community-based design problems and solutions.* This eagerness has created a few outcomes. Students are self-motivated as they have the ability to engage in areas in which they are enthusiastic to concentrate. PBL students take pride in their work, which is partially due to their interest in being involved.

Additionally, the student is more interested in the involvement of community-based projects. When comparing student interest and performance between community projects versus "institutional partners", it was apparent that the students are exceedingly more invested in the project when they can empathize with the project goal and are instrumental in making an impact in a community initiative. This is a critical component to project selection, as both the students and the client are benefited.

A typical competence realized, consistently proven based on provided feedback from the industry, are the soft skills which are intuitively realized by working on a team project. Students who undergo the PBL program are forced to exercise numerous soft skills throughout project phases, including but not limited to; communication, decision making, self-motivation, leadership, time management, problem-solving, and creativity. Many of these skills are not easily achieved in a traditional classroom as the structure cannot provide these various moments of interaction. When students are participating in PBL, they are regularly practicing each of these soft skills in order to meet the needs of the project.

Operating in a similar manner as an office, PBL students are communicating with one another, clients, and industry partners, developing strong verbal skills and professionalism. They are making thoughtful decisions for the project to keep momentum, many of which require strong and creative problem-solving skills. Time management is practiced through "class deliverables" and through accountability to the student's client. Many students are required, in some capacity, to take on a leadership role. Examples might include; construction lead, design lead, energy lead, structure lead, procurer, estimator, etc. This allows specific students to have the primary responsibility of a designated project scope. Their peers rely on them to make the project successful, as many project roles impact another scope or areas of the project. This requires the team to trust one another and to motivate one another. Self-motivation might be the most complex learning outcome/practice to encourage and implement, as it seems to be a skill that is dependent on many personal variables.

While PBL seems to provide students exciting educational opportunities, it is still their own decision to be motivated. The majority of PBL students find avenues to be highly motivated in various capacities. PBL operates as an office environment more so than a traditional classroom. The students have designated class time (Monday, Wednesday, and Fridays from 12:00 pm - 05:00 pm), which is heavily utilized as self-directed work periods. Faculty are not typically lecturing during this course time, but rather make the rounds of the office/job site to support students on an as needed basis. Students tend to appreciate the opportunity to take their own initiative and have “job assignments”. This self-directed office environment creates students who appreciate education from a unique perspective, by creating a culture which expects students to be responsible for their own learning outcomes, with the support of faculty for direction.

A more apparent positive outcome is the opportunity PBL provides to create an interdisciplinary experience. The majority of our students are either Building Science majors (with concentrations in Architectural Technology and Design, Construction Management, or Sustainable Building Systems) or Sustainable Technology majors. Other majors have been involved in various capacities, such as Interior Design, Industrial Design, Marketing, Business, Graphic Design, and Apparel Design.

PBL students may find interest in areas they might not have explored in their designated discipline track. By having a project to explore diverse fields, students are allowed to glimpse into a wide array of career paths. This exploration, finds some students unexpectedly learning what they want to do or even equally as significant, what they do not want to do.

Additionally, this interdisciplinary approach gives students a broader perspective. Where traditional courses segregate concentrations, providing narrow views, interdisciplinary courses entangle each concentrations mentality, decision-making process and reasoning. This creates professionals that are open minded and willing to learn from one another. It allows designers to see into the mentality of an engineer or builder: why the schedule matters thus why design is urgent, why the design details impact the budget, why the details impact the efficiency of installation. It allows builders to see into the intent of the designer: why the design matters to the users, why the construction drawings are drawn for a reason (to be implemented not disregarded), and the importance and intention behind every design decision. It allows the engineers to see into the vision of the builder and designer: how the systems can be integrated into the design, how the systems can influence design details. PBL allows students to practice one another's expertise, so they can be better builders, designers, and engineers, through understanding and respecting one another's reasoning.

More so, interdisciplinary experiences have proven to develop more highly marketable students. They are able to enter the industry with a larger array of skill sets, in assorted industry fields. This affords the opportunity to change fields easily in the event of a change of interest, or change of market, or interest to learn multiple disciplines in the industry. PBL students tend to be unique employees that employers seek after as they are both proficient and versatile. Other authors have also discussed how PBL improves student learning and prepares graduates for professional practice including such benefits as: teamwork skills, increased student motivation, articulation between theory and practice, and problem solving (Fernandes, 2014).

Opportunities

These positive outcomes have prompted a further consideration, should students be exposed to PBL earlier in their curricular path? If one year can foster this level of effectiveness, what would be the outcome of implementing a piece of this methodology sooner? This could address a few opportunities. 01. Students might find their area of interest sooner through exploration of various career paths, allowing them time to change their majors or concentrations. 02. Pairing younger and older students would promote an office environment where students may support one another, mentor and mentee approach. 03. If younger students shadowed older students, their understanding of expectations could change the caliper of expectations for the remainder of their educational career.

Much like an office, PBL classrooms require a unique form of evaluation, one which is prominently qualitative. This transition for students, from quantitative to qualitative feedback, can be difficult to accept and fathom, as students are eager to see a grade with each assignment. With project based learning, each student has many individual and group “assignments” with ranging deadlines. This is one of the most complex aspects of PBL. How do instructors fairly evaluate and provide an appropriate amount of feedback? Each cohort, grading is tweaked to compliment the project. However, most often the PBL students have been graded individually based on performance towards major project milestones. Typically, students meet with the faculty at multiple points in the year to discuss their individual performance and have an opportunity to ask questions.

Additionally, students track their work weekly in the form of a timesheet and a weekly reflection. The timesheets are ways for the students to visually realize their hours and for instructors to understand how many and how hours were utilized. The timesheets are also a professional expectation for the students to hold accountability to their client. In the weekly reflections, students are given the opportunity to both reflect, provide faculty insight, and vent on the week's successes and difficulties.

How can qualitative data be evaluated to confirm all learning objects are being achieved? The PBL has not yet implemented a method to integrate measurable metrics for learning outcomes. While students are certainly learning through unique experiences and gaining necessary professional soft skills, it is still to be determined if PBL students are equally collecting the same learning outcomes as required in a traditional course track. This current fall semester of 2017, student’s depth of knowledge in traditional construction project planning and scheduling methods and techniques will be compared through standardized testing.

Is PBL feasible and sustainable for both faculty and students? PBL has proved to be a challenging workload students with the demanding time and energy required to make the project successful. Many students struggle to find a balance and compete with other responsibilities such as traditional coursework, extracurriculars, part-time jobs, etc. By the end of major deadlines and semesters, the students are drained. Fernandes, 2014 also noted that some students complain that PBL creates too large of a workload (as compared to traditional teaching. Additionally, this same time and energy requirement directly impacts faculty. The preparation and implementation of project based learning requires extensive time and commitment, and when paired with a regular course load, is not sustainable for faculty to maintain. This workload issue must be solved through proper project scope creation that allows for reasonable work and completion during the academic cycle.

One other potential solution to keep students from being overwhelmed, is to provide them with a smaller PBL opportunity earlier in their academic careers. This could prevent the initial feeling of being overwhelmed by an open ended design problem and allow the students to be more effective earlier in the time-frame of the larger PBL experience. Using problem based learning early in the process as a support for future, larger scale project based learning was suggested by (Chinowsky et al, 2006). Where problems are considered to be much smaller, more focused and more trackable design exercises than projects.

Maintaining support for the resources necessary for PBL is an ongoing effort. These projects require various resources including; a high bay building with office and meeting spaces, tools, model making materials, building materials, computers and specialized software programs, funding for research and exploration, truck(s) and trailers.   The original pilot, funded by the National Science Foundation TUES grant, supplied financial resources to jump-start the program, the long term expenditures have been more cumbersome to sustain. While some of these resources are supported by the client, the operational costs are difficult to bear without additional sponsors, Departmental, and College support.

PRACTICAL APPLICATION OF PBL IN BUILDING SCIENCE EDUCATION

Is PBL a useful teaching tool for building science education? PBL is very well suited to improving overall student learning outcomes for building science students since PBL has been shown to improve student learning/retention and prepare graduates for professional practice including such benefits as: teamwork skills, increased student motivation, articulation between theory and practice, and problem solving. Building science is an applied profession and as such students should be exposed to projects involving real buildings.

How then to implement PBL into a residential focused building science education?

- Problem of motivation-- must have a meaningful problem and best to have a real client. Develop a cache of contacts and potential projects early in the process so that an appropriate building science project is always ready for the incoming student cohort. Suggestions include working with local communities and organizations such as Habitat for Humanity. Another motivational scheme to consider is more extensive use of modern media tools. A key aspect of modern media (such as social media) is that communications are two way and often real-time. Whereas current/traditional teaching even with online platforms such as moodle and blackboard tends to be passive for students with one-way communication from the professor to the student or from the textbook to the student--- this two-way interactive communication can be developed in wiki's and other tools as suggested by (Chu et al, 2017).

- Problem of students feeling overwhelmed-- start with problem based learning. Suggest having smaller problem based learning experiences early in the curriculum such as building energy audits or assessments of moisture problems in existing structures. Larger problem based learning experiences are reserved for final year capstones. However, the potential exists to allow younger students to participate in limited roles in the final year capstone-- allowing seniors to expand their management role and giving younger students another opportunity to become familiar with PBL in a less demanding capacity. The same co-teaching opportunity exists if the department has a graduate program. Graduate student can coach final year students as well.

- Problem of assessment--provide frequent opportunities for formative self-assessment and revision. Instructors should provide opportunities for detailed discussion of student progress and performance and give the opportunity for students to give feedback on the both the problem and the instructor's performance. However, such detailed discussions are too time consuming to carry out on a frequent basis (perhaps only a midterm discussion and final wrap-up are possible). In order to give more frequent opportunities for assessment, self-assessments and joint-peer assessments can be implemented. The self assessment can take the form of a weekly reflective writing exercise.

Many of the methods and solutions suggested above were also suggested by (Barron et al, 1998) who proposed the following four curricular design principles; must set learning-appropriate goals, must have scaffolds that support both student and teacher learning (such as using problem based learning first as an introduction to PBL, have frequent opportunities for formative self-assessment and revision, and create both external and internal social organizations that promote participation and result in a sense of agency (such as setting up student teams properly and having an appropriate "client" that will get students motivated).

CONCLUSION

The implementation and practice of PBL in a Building Science curriculum at Appalachian State University has presented many strengths and opportunities and is an ongoing endeavor. Our faculty is committed to further exploration PBL. As we continue this journey, we will seek to confirm the seeming benefits in student learning outcomes, find ways to scope/scale the projects to avoid overworked students and faculty, and find innovative ways to allow all of the students in the program to be engaged in a thoughtful and extensive project based learning experience before they graduate and move into the workforce.

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Building Envelope as an Effective Strategy for Achieving Sustainable Building Energy Efficiency

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ABSTRACT

The energy performance of building is closely linked to the energy performance of building envelope. Besides, it is important to understand the energy performance of building envelope in order to achieve building efficiency and proper building energy management. Energy-conscious buildings are becoming an important part of design helping to minimize demands on non-renewable resources while providing better natural ventilation than was previously possible. At present, new renewable energy sources such as solar, wind, wave, tidal, ocean, thermal and nuclear power are now being used to supplement fossil fuels. However, their production is still capital intensive and the wide use of fossil fuels, to some degree, has polluted the atmosphere. Besides, considering the urgency of saving the world's energy reserve. As such, the current research was undertaking to investigate and recommend effective passive strategy for achieving sustainable building energy efficiency. In order to achieve this aim, the study investigated the impact of building envelope systems such as roof and wall design solutions on the building energy efficiency through experimental approach using three building physical models attached with air-conditioning system each. Subsequently, the performance of the building envelope physical models in terms of energy consumption, cooling load, indoor temperature, indoor relative humidity, indoor comfort conditions were monitored through Lascar EasyLog USB-2-LCD data logger sensors and Multifunctional Mini Ammeter. In the results, Insulated building envelope wall and roof systems emerged as effective passive strategies for achieving sustainable building energy efficiency.
Key Words: Sustainable, Energy, Performance, Building, Envelope, Insulation

1. Introduction

The sustainable performances of building envelope are closely linked to the energy performance of building envelopes. As such, it is important to understand the energy performance of building envelope in order to improve building envelope sustainable performance and design. Building envelopes being the largest component of building consumes large amount of energy and other resources at each stage of its development from design, construction through to operation and final demolition (Cole and Rousseau 1992; Hui 2001). The energy consumption at each stage in the building envelope development is largely influenced by how the envelope was constructed, used and how the energy was used (Spence and Mulligan 1995; Jamie 2007). The actual amount of energy consumed by building depends on many factors such as the building design itself, building envelope design, building orientation, outside temperature, window areas, light systems, air conditioning and ventilation, level of insulation and the thermal characteristics of building envelope i.e. walls and roofs (Ding 2004; Jamie 2007). Besides, the cooling energy needed by building can be significantly reduced with proper insulation of building envelope through wall and roof components (Irene and Robert 2007). Also, the solar heat gain and cooling energy consumption in building can be significantly reduced using lighter colored building envelope. Moreover, improving the energy efficiency of the building envelope glazing system will bring about reduction in energy consumption and improvement in building energy efficiency (Stansfield 2001). Building envelope can also impact overall building energy consumption through its shading devices (Irene and Robert 2007). In the study conducted by Cheun et al. (2005) using the passive thermal building envelope design strategies together, such as insulation, colour, glazing system and shading devices, it was found that the annual required cooling energy felt from 3056KWh to 2252KWh. Considering the urgency of saving the world's energy reserve, energy-conscious buildings are becoming an important part of design helping to minimize demands on non-renewable resources while providing better natural ventilation than was previously possible (Brown and Herendeen, 1996). As such, it is important to understand the energy saving potential of the building envelope in energy conscious building design. The energy performance of building envelope has direct influence on the level of energy consumption of building. It is therefore necessary to consider building envelope as effective sustainable passive strategy for achieving sustainable building energy efficiency.

Moreover, as the energy use in the building accounts for a larger part of the word's total energy use and greenhouse gas emissions, there is need to improve the building energy efficiency through thermal insulation. This improvement requires the highest possible insulation resistance, new insulation materials and solution with low thermal conductivity values (Sharma 2013). According to this author, building energy efficiency can be improved by implementing either active or passive energy efficient strategies. Consequently, there have been increased interest in passive building energy efficient strategy. This passive strategy is being seen as viable solution to the problem of energy crisis and environment pollution. Several researchers around the world have conducted studies on the improvements in the building envelope and their impacts on building energy efficiency. According to Sharma (2013) energy savings of 31.4% and peak load saving of 36.8% were recorded for high rise buildings by implementing passive energy efficient strategies. The strategies include adding extruded polystyrene (XPS) thermal insulation in walls, white washing external walls, reflective coated glass window glazing, 1.5m over hangs and wing wall to all windows (Cheung et al. 2005). In another study, the energy effective building envelope design was found to have saved as much as 35% and 47% of the total energy and peak cooling demands respectively (Chan and Cow 1998). In Greece, the thermal insulation in walls, roof, floor, and low infiltration strategies were found to reduce energy consumption by 20-40% and 20% respectively. According to the same study, light colored roof and external walls reduced the spaced cooling load by 30% and 2-4% respectively (Balaras et al. 2000). Thus shows that building envelope has a significant impact on the overall building energy consumption and efficiency. Hence, the current research was undertaking to investigate and recommend effective sustainable passive strategies for achieving sustainable building energy efficiency in hot climatic region such as Trinidad and Tobago.

2. Model Description

2.1 Building envelope systems insulated with fibre glass

The study investigated the impact of building envelope systems such as roof and wall design solutions on the building energy efficiency through experimental approach using three (3) building physical models attached with air-conditioning system each. The three (3) identical small scale test models (1.524m long x 1.219m wide x 1.524m high) were built to determine the effect of the different envelope design solutions in the building energy efficiency performance. The difference between the models is the type of masonry wall and roof materials used. In the process, eleven (11) different model designs were tested as described below. The testing was done in two phases: Phase 1- building envelope insulation, and Phase 2- roof system insulation. In the phase 1, three model design solutions were tested. The models include: Models A, B and C as shown in Figure 1, they were constructed with 100mm concrete block, 150mm concrete block, 100mm clay, clay tile roofing system, corrugated standing steam roofing system, galvanised iron roofing system, steel frame structure, wood roof frame structure, 100mm concrete slab, 12 BTU Panasonic air conditioning system and 1.5 inches Fibre glass insulation for wall and ceiling. The envelope design solutions, were compared with each other to determine their benefits and impacts to the building energy efficiency and impacts to the building energy efficiency.

Model A: 100mm concrete block envelope mode with red clay tile roof

Model B: 100mm clay block envelope mode with corrugated standing steam sheet

Model C: 150mm concrete block envelope mode with galvanized aluzinc sheet roof

Steel frame

Figure 1.   Physical building envelope models

2.2. Roof systems with fibre glass insulation

In the second phase, five (5) model designs were tested based on three identical models as shown in Figures 2, 3 and 4. The models were constructed with 150mm concrete block, 100mm clay, corrugated standing steam roof, corrugated galvanised iron sheet roof, 100mm concrete roof, steel frame structure, wood roof frame structure, 100mm concrete slab, 12 BTU Panasonic air conditioning system and ceiling insulated with 1.5 inches Fibre glass. The models were tested with and without insulation, with and without air conditioning system to develop baseline conditions which would be used to determine the benefits of the roof materials, roof system and the insulator to building energy efficiency.

Figure 2. Model 1 - 100mm Clay block walls and corrugated galvanised iron sheeting roof

Figure 3. Model 2 – 150mm Concrete block walls and corrugated standing seam roof

Figure 4. Model 3 - 150mm Concrete block masonry walls and concrete roof

2.3 Experimental Methodology and Procedures

The models in each phase were tested at same times and subjected to same environmental conditions. Subsequently, the performance of the building envelope physical models in terms of energy consumption, cooling load, indoor and outdoor temperature were monitored through Lascar EasyLog USB-2-LCD data logger sensors and Multifunctional Mini Ammeter. This was aimed at monitoring the impact of outdoor temperature and humidity on the envelope energy consumption and indoor temperature. Also, these parameters were monitored in January, March and June with A/C and without AC. In the process of monitoring, each envelope model was tested for 2 days with air conditioning (A/C) for three months, while the mini ammeter measured the cumulative energy consumption in kWh at interval of 2hrs. Air conditioning unit was incorporated into the experiment in order to investigate the impact of building envelope materials on the envelope energy efficiency performance. This was done by measuring the energy consumption associated with each envelope model tested. Along with the Multifunctional Mini Ammeter reading, Lascar EasyLog USB Data Logger sensors were also installed on the outside roof, outside west wall and inside west wall of the models to monitor outdoor and indoor humidity and air temperature. The logger sensors were set to record humidity and air dry bulb temperature information at the time interval of 5min for 2 days continuous reading with air conditioning cooling. Hence, a summary of the insulations and materials used for the different masonry unit walls tested are presented as follows in Table 1 for phase 1 and Table 2 for phase 2.

Moreover, the parameters related to type of external walls and their insulation that influenced the internal environment were identified as Relative Humidity and Temperature. For each model, these parameters were tested every 5 minutes for 2 days over a period of 48 hours, both with and without Air Condition. The energy consumption was measured every 2 hours over the 48-hour period for two days in three months when the models were tested with Air Condition. This would enable correlations with the insulation and the energy consumption necessary to achieve energy efficiency.

Table 1. Components and material used in the envelope physical models

Components	Model A	Model B	Model C
Roof Sheeting	Red clay tile	26G corrugated standing seam sheeting	26G galvanised aluminium sheeting
Roof Frame	2" X 4" Timber	2" X 4" Timber	2" X 4" Timber
Structural Frame	4" steel RHS	4" steel RHS	4" steel RHS
Ceiling	6mm plywood ceiling board and 1.5"fibre glass sheet	1.5"fibre glass sheet	1.5"fibre glass sheet
Floor **Floor finishes**	4" concrete slab Carpet	4" concrete slab Terrazzo	4" concrete slab Wood
Wall **Wall insulation**	100mm x 200mm x 400mm concrete block 1.5"fibre glass sheet	100mm x 200mm x300mm clay block 1.5"fibre glass sheet	150mm x 200mm x 400mm concrete block 1.5"fibre glass sheet

Table 2. Materials used in model 1, model 2 and model 3 under insulated roofing systems

Member	Model 1	Model 2	Model 3
Roof Sheeting	Corrugated Standing Seam galvanised sheeting	26G Corrugated galvanised iron sheeting	100mm concrete slab roof
Roof Frame	2" x 4" Timber	2" x 4" timber	2" x 4" timber
Frame	4" Steel RHS	4" steel RHS	4" steel RHS
Floor	4" concrete slab	4" concrete slab	4" concrete slab
Masonry Wall Units	150mmx200mmx400mm Concrete block	100mmx200mmx300mm Clay block	150mmx200mmx300mm Concrete block
Wall Insulation	No Insulation (Model 1.1)	No Insulation (Model 2.1)	No Insulation (Model 3)
	1 ½" Fiber Glass Sheets (Model 1.2)	1 ½" Fiber Glass Sheets (Model 2.2)	-

The data collected for concrete and clay masonry unit walls were analysed and compared to determine which insulation performed the best for each wall. Likewise, the data collected from these roof systems were analysed and compared to determine which insulation performed the best for each roof. Each model was tested for two days with Air Condition and two days without Air Condition. The models were tested at same time period under same external environment conditions. The research parameters were monitored using the Lascar Easy Log USB-2-LCD Humidity, Temperature and Dew point USB data logger sensors. the energy efficiency performance of each physical envelope model was measured using Multifunctional Mini Ammeter. The following sections present the analyses of the data collected.

3. Data analysis and results

3.1 Energy efficiency performance of insulated building envelope

The average energy consumption data for the models were collected at two hours' interval over a 48 hours (2 days) period. The result shows in Figure 5 that the energy consumption of the models increases as the outside temperature increases and decreases as the levels of the sun exposure decreases. The result further shows that the energy consumption of the models was at the peak between the hours of 10.00am to 4.00pm. In these specified periods, the average energy consumption of Model "B" was the lowest with 0.3420 kWh while Model "C" has the average energy consumption with 0.4683kwh. This indicates higher energy efficiency performance in Model "B" when compared with other two models.

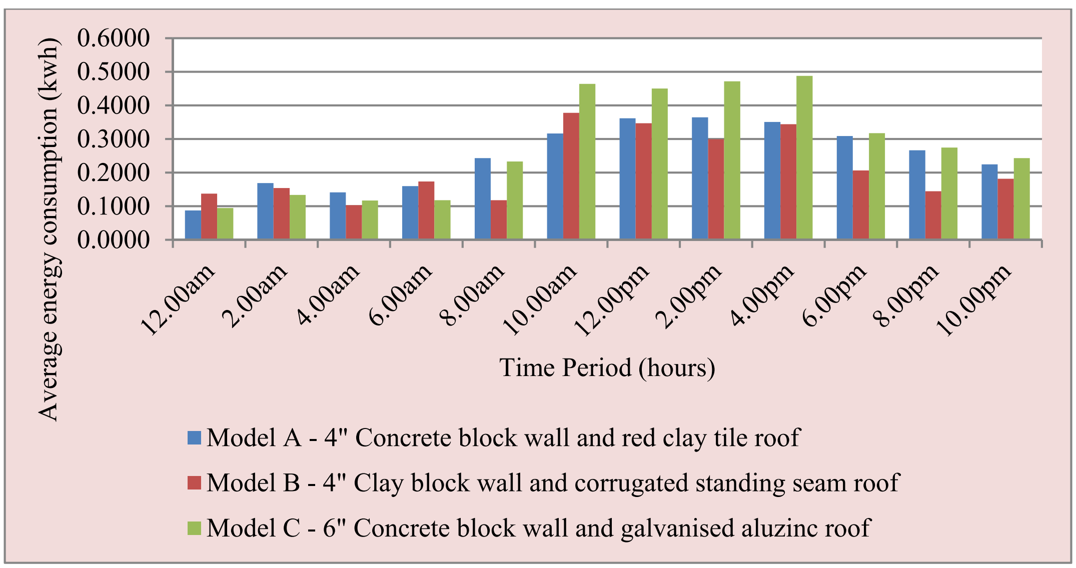

Figure 5. Average energy consumption at two-hour interval for 2 days (48hours)

Besides, it can be seen that more energy was consumed between the periods of 6.00pm-10.00pm than the periods of 12.00am- 8.00am. This is because the building envelope stores heat energy during the period of 6.00pm - 10.00pm and releases the heat energy during the periods of 12.00am – 8.00am for cooling and temperature stabilization. Moreover, the energy consumed between the periods of 12.00am – 8.00am was lower due to the absence of solar radiation from sun and low heat gain into the envelope indoor environment. The result further revealed that energy consumption was greatest in Model 'C" during the day with highest thermal mass of 150mm (6") concrete block wall, while Model "A" has the highest energy consumption during the night due the presence of thermal mass in the100mm (4") concrete block wall and red clay tile roof. This means that more energy is stored at night in model "A" than the other two models.

Moreover, given the set indoor temperature at 24ºC as shown in Figure 6, model B recorded the lowest indoor temperature when compared with other two models indoor temperature profile performance. The Figure shows that, within the peak period between 10.00am – 4.00pm, the indoor temperature of model B was the least among the three models tested with about 2ºC above the 24ºC set indoor temperature at its peak temperature. Besides, model B consumed the least amount of energy to cool the outdoor temperature to the indoor temperature of 26ºC at its peak temperature when compared to the other two models. This suggests better energy efficiency performance of model B. This is because the model was able to reduce the impact of outdoor temperature. In addition, model B continues to maintain the least temperature even after the outdoor temperature and sun radiation started to decline between 8.00pm – 12.000am.

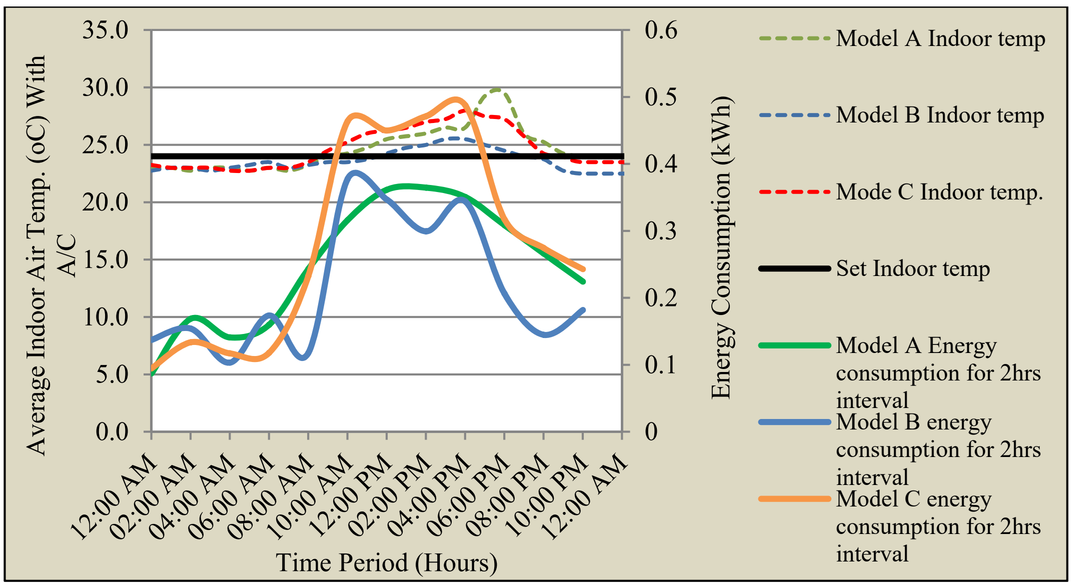

Figure 6. Energy consumption and indoor air temperature

3.1.1 Energy consumption and relative humidity performance of the models

Indoor relative humidity represents the percentage of the available energy that has been used for cooling. In model C, the indoor relative humidity was as high as 90% during the peak period of 10.00am to 4.00pm, while model A was relatively at 62% and model B was at 60% as shown in Figure 7. This means that significant percentage of the available energy from electricity has been used for air cooling in model C as compared to mode A and B where lesser amount of energy was used for cooling. Moreover, given the recommended set indoor relative humidity of 60% with A/C, model B recorded better performance when compared with model A.

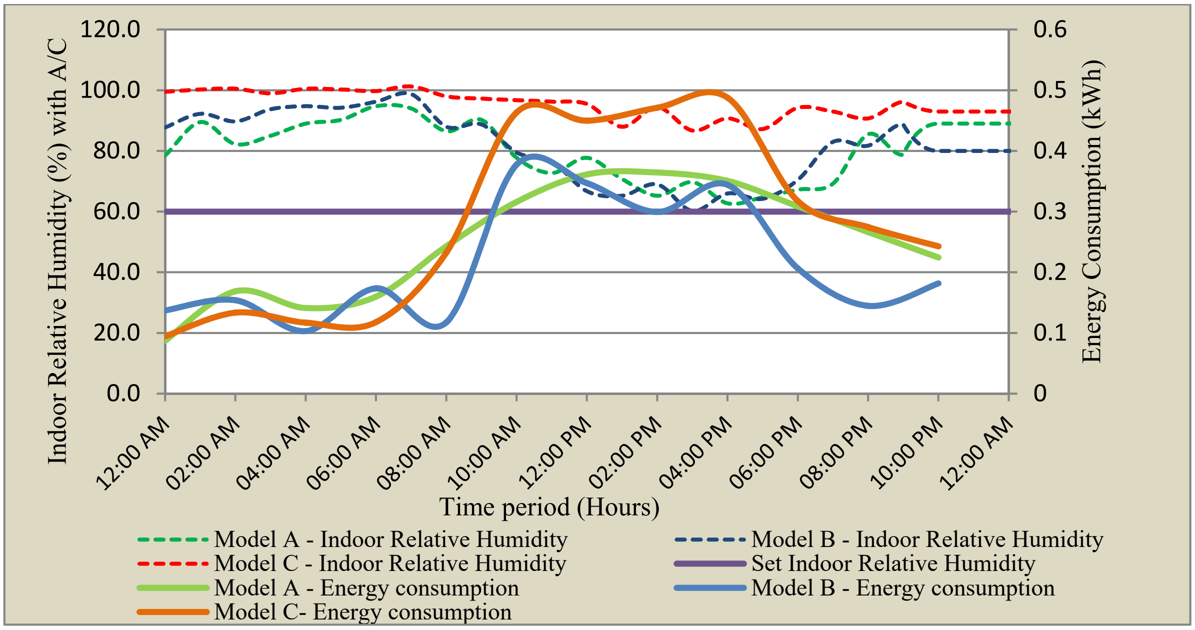

Figure 7. Energy and Indoor relative humidity

This suggests better indoor thermal comfort conditions in model B in terms of indoor temperature and indoor relative humidity as shown in Figure 7. On the other hand, Figure 8 shows the relationship between the outdoor relative humidity and the energy consumption. In this case, the outdoor relative humidity represents the percentage of the available energy for cooling. Figure 8 shows that between the periods of 12.00am to 8.00am, the average outdoor relative humidity of the three models was high ranging from 80 % - 100% while the energy consumption rate of the three models was low, ranging from 0.1 to 0.2 kWh. This means that the percentage of the available energy for cooling is very high between the periods of 12.00am to 8.00am.

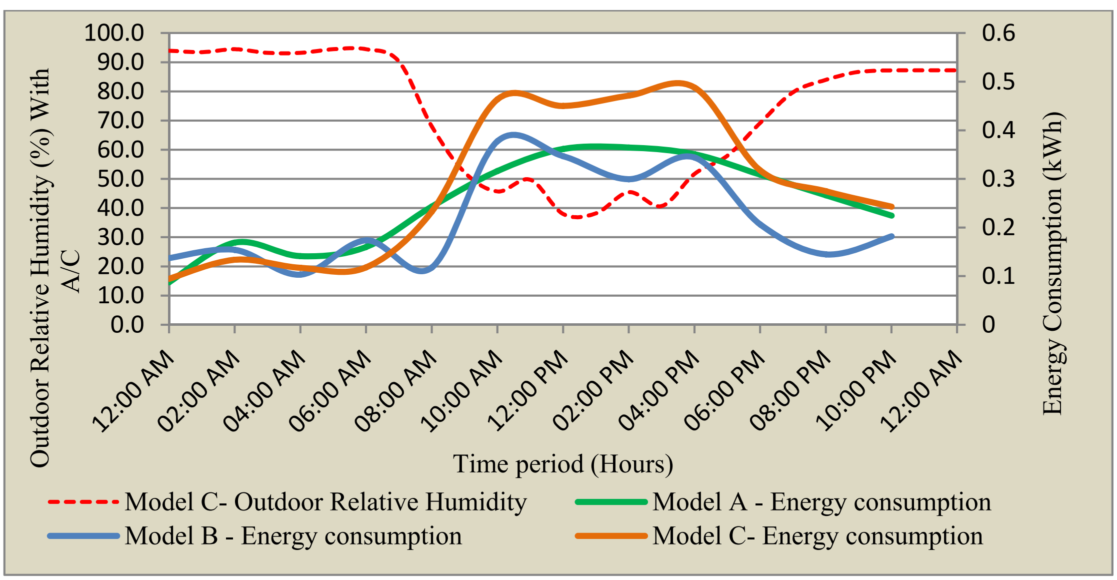

Figure 8. Energy and Outdoor relative humidity

Moreover, as the solar radiation increases, the outdoor temperature increases and the energy consumption also increases, while the outdoor relative humidity decreases. Thereby reduces the available energy for cooling between the periods of 10.00am to 6.00pm. Within these periods, model B recorded the lowest energy consumption, compared to the other two models with 40% outdoor relative humidity. This means that Model B has more energy available for cooling than model A and C. This suggests that model B is more sustainable in terms of energy efficiency and relative humidity performance.

3.2 Energy efficiency performance of insulated roof systems

From this data set, average energy consumption over a 24-hour period was computed. The results for the five (5) models in Figure 9 show relatively similar trend-lines for progression of energy consumption throughout the 24hrs time period. For the period 6-12 (morning) consumption consistently increased along exponential trends, peaking between 12-15 (midday to mid-afternoon), after which consumption gradually decreases along a gentler inverse exponential trend into the nighttime period, up to approximately 24 (midnight). Between 24 (midnight) and 30 (sunrise) consumption remains constant. Considering the energy consumption for the 18-24 period, it can be inferred that the models still require a significant amount of cooling after sunset to achieve thermal acceptability of the internal environment. Moreover, with the aid of the thermal mass of the material components of the envelope, heat energy produced by the sun is absorbed and stored by the models during the day and released to the internal and ambient at night when external temperatures drop. At this time the envelope functions against the cooling of the interior in dissipation of heat from the internal outwards, is limited, thus necessitating mechanical cooling, for achievement of thermal acceptability.

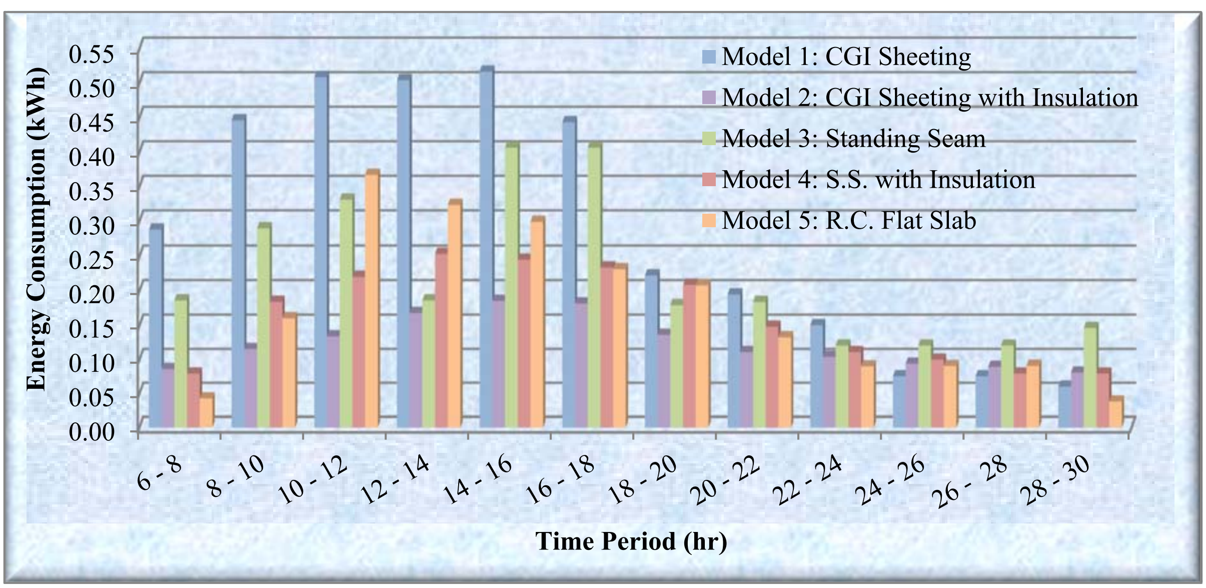

Figure 9. Average Energy Consumptions for Tested Roofing System over a 24hr period

Besides, the consistency of consumption between 24-30 (midnight to sunrise) indicates that the heat source (building envelope) has dissipated most of the heat energy stored during the daytime period and a state of relative thermal equilibrium was achieved, thereby necessitating minimum and consistent function by the air conditioning. Further analysis of data presented in Figure 9 shows that the bulk energy consumption (approximately 60% - 70%) for each model was engaged during the 6-18 period (daytime period) where cooling requirements are most significant. Upon removal of an external heat source (i.e. the sun), the models, were seen to engage the remaining 30% - 40% of the total energy consumed for the 24hr. period. This is attributable to lower external air and surface temperatures, and the relatively minimal heat gains from the environment.

In the case of the findings displayed in Figure 10 on the model energy consumption performance ranking, it can be seen from the figure that daytime (6-18) consumptions for each model are consistently greater than those for the nighttime periods (18-30).

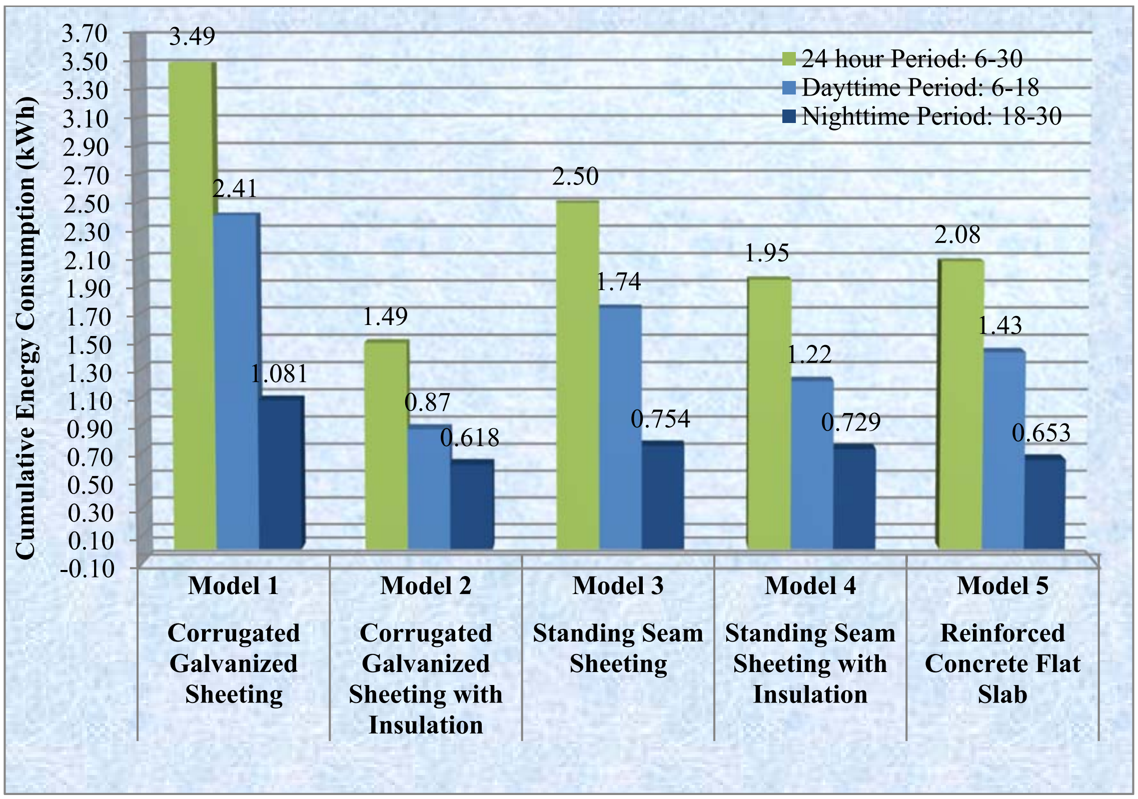

Figure 10. Cumulative average energy consumption for tested roofing systems

Ranking of each model with respect to efficiency of cumulative energy consumption shows model 2 with corrugated galvanized sheeting roof system and insulation consumed the least energy and emerged the most efficiency. It can be seen in the cumulative energy consumption performance that the roofing systems with insulation (Models 2 and 4) are more energy efficient than their counterparts without while concrete (Model 5) deemed a relative mid-range performance. Considering the insulated systems, Corrugated Galvanized Iron (C.G.I) (model 2) outperforms Standing Seam roofing system (model 4). However, in Figure 11, the reverse is shown for the un-insulated counterparts as Standing Seam is proven to outperform the C.G.I. system. Moreover, in terms of the average rate energy consumption, Model 4 with standing seam sheeting roof system was more energy efficient than Model 2 with insulation.

Energy consumption rates during the daytime period can be seen to be significantly greater than at night as the required cooling load is greater in the daytime than at night. Moreover, the energy consumption at night is not solely a function of required cooling load, but also minimum operating requirements of the air-conditioning. With respect to their energy efficiency (rate of energy consumption) the insulated roof systems are observed to outperform all other roof systems tested; Standing Seam with insulation (0.072 kWh/°C) followed by C.G.I Sheeting with Insulation (0.088 kWh/°C). Reinforced Concrete Flat Slab is deemed the mid- range performer (0.89 kWh/°C) followed by the un-insulated models, whereas with their insulated counterparts, Standing Seam (0.092 kWh/°C) was rated more efficient than C.G.I. (0.134 kWh/°C). Overall, both by C.G.I Sheeting with Insulation and Standing Seam with insulation performed best in terms of impact on the building energy efficiency. These roofing systems can be recommended as effective and sustainable passive strategies for residential building energy efficiency.

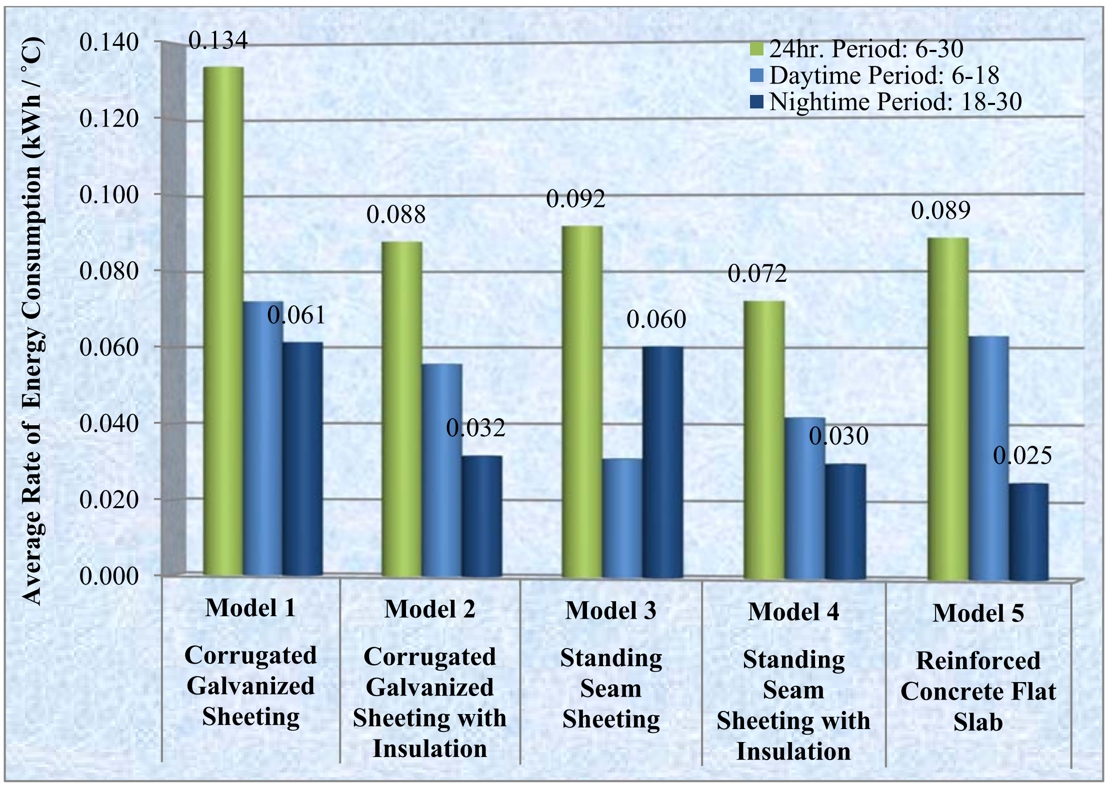

Figure 11. Average Rate of Energy Consumption for Tested Roofing Systems

3.3 Social economic benefits of building envelope roofing systems

The need for generation of the tangible implications of these findings for the thermal and energy consumption for each envelope systems tested was deemed of paramount importance. In the case of the roofing systems, the projected financial demands associated with energy consumption for each model tested and the relative cost savings which may be realized were established as shown in Table 3. The following base assumptions were utilized for the financial calculations: Average Daily External Temperature = 29.6 ˚C (Average of Measured

Values) and Unit Cost for Electricity = $0.26 per kWh. While the following average lifespans, derived from literature, are assumed for the roofing systems under investigation:

- Corrugated Galvanized Iron Sheeting System: 25 years
- Standing Seam Sheeting System: 50 years
- Reinforced Concrete Flat Slab: 150 years

For the model constructed Table 3 shows that over a 150-year period (estimate lifespan of a residential structure), the C.G.I. sheeting system (Model 1) proves the most expensive to cool. This system is considered to be the conventional system and thus the baseline model. In comparison the baseline model it can be seen that the other systems offer a 30-45% reduction in cost.

Table 3. Cost Projections for Energy Consumption of the Tested Roofing Systems

Roofing Systems		**C.G.I. Sheeting**	**C.G.I. Sheeting with Insulation**	**S.S. Sheeting**	**S.S. Sheeting with Insulation**	**R.C. Flat Slab**
		Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Avg. Rate of Energy Consumption for 2 hr. period (kWh/°C)		0.134	0.088	0.092	0.072	0.089
Avg. Daily Energy Consumption (kWh/day)		8.904	5.847	6.114	4.817	5.899
Cost of Energy	Daily ($/day)	2.320	1.520	1.590	1.250	1.530
	Annual ($/yr.)	845.610	$555.270	580.630	457.410	560.160
	Lifespan ($/150 yrs.)	126,841	83,289	87,094	68,611	84,023
Relative Cost Reduction for Research Model ($)		-	7,259	6,624	9,705	7,136
Relative Cost Reduction		-	34.3%	31%	46%	33.8%
Energy Consumption Rating		5	2	4	1	3

In all, Standing Seam with Insulation proving the most energy and cost efficient with reference to pure energy consumption. Standing Seam with Insulation (Model 2) initiated a cost savings of approximately 46% of the expenditure of Model 5. C.G.I. with Insulation followed closely by Reinforce Concrete (R.C) Flat slab result in a comparative 34.3% and 34.8% cost savings respectively compared to conventional model 5, while, the un-insulated Standing Seam is the worst comparative performance. However, achieved a 31% reduction in operation costs. Moreover, in Table 4, financial projections for the research model over a 150-year lifespan portray a slightly dissimilar ranking of efficiency of the roofing systems in comparison to the findings of energy consumption. When the average/anticipated lifespan of each system is taken into account, it is realized that all systems do not have the longevity to endure the entire 150-year time period and as such will warrant replacement multiple times during this tenure.

Table 4. Projected Life Cycle Costing for Roofing Systems and Associated Energy Consumptions

	Roofing System	Model 1: CGI Sheeting	Model 2: CGI Sheeting with Insulation	Model 3: Standing Seam	Model 4: S.S. with Insulation	Model 5: R.C. Flat Slab
	Primary Capital Expenditure	996.66	1,092.66	1,181.46	1,277.46	2,682.09
	Estimated Lifespan of System	25	25	50	50	150
150 Year Period	Cycles per Period	6	6	3	3	1
	Infrastructure Upgrade Cost ($)	4,983.30	6,555.97	3,544.38	3,832.38	2,682.09
	Cooling Energy Costs ($)	126,841.07	83,289.80	87,094.72	68,611.51	84,023.56
	Total Cost of Roofing System ($)	131,824.38	89,845.77	90,639.10	72,443.89	86,705.65
	Cost Comparative (%)	100%	68%	69%	55%	66%
	Financial Efficiency Ranking	5	3	4	1	2

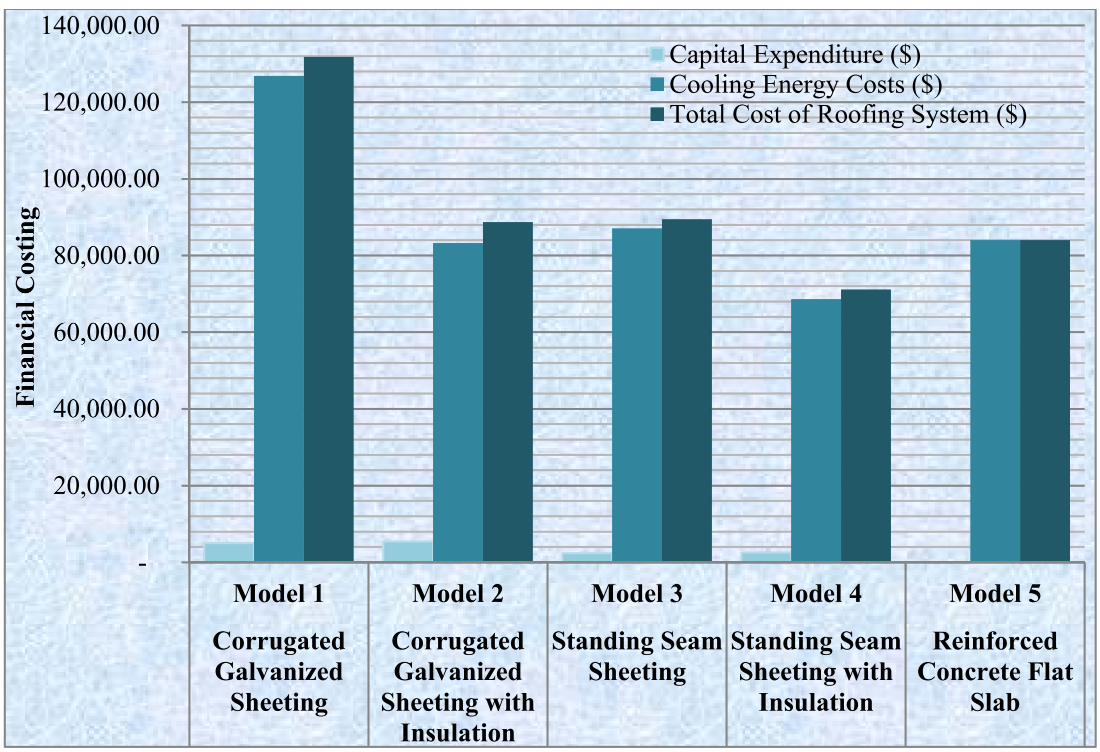

Figure 13. Financial Projections (150-year life span) relevant to roofing systems

Financially, the replacement (demolition of failed systems and construction of new) of these systems result in increased infrastructure costs, which significantly impact the life cycle costing of the model. Although initially the most expensive system installed on the research model (primary capital expenditure), the Reinforced Concrete Flat Slab is actually realized to be the most cost effect with respect to total capital expenditure, when the costs of upgrade/replacement of the other systems are accounted for.

As shown in Figure 12, considering total capital expenditure, it is derived that models 1 and 2 (C.G.I. with and without Insulation) costs roughly 2.2 and 2.4 times that of model 5 (R.C. Flat Slab), while models 3 and 4 (Standing Seam with and without Insulation) costs roughly 1.3 and 1.4 times that of model 5. Results show that when considering the long-term financial implications of the choice of roofing systems, the capital expenditure of model 2 represents a fraction of the total cost associated with the roof made with Flat Slab system (Model 5). Based on cooling energy consumption, the C.G.I. system with insulation (Model 2) was rated more energy efficient than the R.C. Flat Slab system (Model 5). When taking into account the long-term function of the system, it is realized that the relationship is actually inversed and Model 5 is marginally more cost effective in comparison to Model 2 in the long-term. Of notability, is that other than this interchange, the rated efficiencies of the energy consumption and the total projected lifespan cost of the research model, are in concurrence. Overall, standing seam sheeting with insulation, reinforce concrete flat slab and corrugated galvanized Iron sheet roof systems emerged the most cost effective with high energy consumption efficiency.

4.0 Discussion

The difference in temperature between the external and internal environment for the tested envelope systems, without the function of air-conditioning is termed the 'Baseline Thermal Variation. This value is a direct measure of the thermal efficiency of each building envelope system. The ability of the envelope system to limit energy transference from the generally warmer to the cooler environment (along the temperature gradient); thus positively contributing to achieving acceptable levels of thermal comfort for the interior. The baseline thermal variation, is the amount by which the building envelope was able to keep the internal temperature cooler by in comparison to the external during the 6-18 (daytime) period and vice versa for the 18-30 (nighttime) period. Given external temperatures during the daytime was within the upper limit or in excess of the acceptable comfort range, a decrease in temperature is deemed desirable. Besides, ranking of Baseline Thermal Variations and energy consumption rate for the 6-18 (daytime) period for envelope roofing systems show that the insulated models proved the most thermally and energy efficient, with the Standing seam system with insulation (Model 4) followed by the C.G.I. System with insulation (Model 2) being the top performances, affecting the largest reductions of internal temperatures, more energy efficient and thermal acceptability. Reinforced concrete flat slab system (Model 5) was the middle performer, seeming to achieve a balance between the performance of the insulated and un-insulated metal sheeting systems. The un-insulated systems were observed to have affected the smallest temperature differentials, with the Standing Seam system (Model 3) outperforming the C.G.I. System (Model 1), which was the least efficient of all tested systems. The rated relative efficiencies of the envelope roofing systems were found to be in direct correlation, with the findings of the literature review (Sharma 2013) and subsequent theoretical calculation.

Moreover, the building envelope systems would function to limit the transference of energy from the warmer external ambient (presence of the sun) to the cooler interior during the 6-18(daytime) period. However, during the 18-30 (nighttime) period, when external temperatures drop lower than the internal, the building envelope would function at the same rated efficiency but in reverse, limiting dissipation of the stored heat energy (attributable to the thermal mass of the model) from the internal to the external ambient. Evidence of the consistent performance of each roofing system is evidenced as follows: for any model the magnitude of internal temperature decrease observed for the 6-18 (daytime) period, is near equal to the magnitude of internal temperature increase observed for the 18-30 (nighttime) period. It can thus be deduced that the insulation utilized for the metal sheeting systems provides beneficial thermal regulation during the daytime and has an inverse effect at night. For rating purposes, the 6-18 (daytime) period is determined to be the dominant efficiency rating of Baseline Thermal Variation, as it is given a heavier significance rating. The significance weighting of the 6-18 (daytime) period out ranked that of the 18-30 (nighttime) period. This is because the magnitude of external temperatures during the day were significantly higher than those at night. This meant that the effect of insulation was more critical towards achieving thermal efficiency during the 6-18 (daytime) period compared to the 18-30 (nighttime) period, where external temperatures are comparatively closer to achieving acceptable values for thermal comfort.

It is very important for passive housings and eco-friendly building concepts such as sustainable envelope, wall and roof passive strategies to be implemented. According to this study, the tested passive sustainable strategies have been found to be effective in the realisation of the building energy efficiency. Prominent among them include: Standing Seam roofing sheet insulated with fibre glass, corrugated galvanised roofing sheet insulated with glass fibre, reinforced concrete flat slab roof, concrete block wall internally insulated with fibre glass, clay block wall internally insulated with fibre glass, and building envelope systems insulated with fibre glass such as Clay block wall insulated with fibre glass, corrugated standing seam sheet insulated with fibre glass, Terrazo floor finishing, and 100mm concrete slab. According the above analyses, these passive strategies were found to be the most effective energy saving strategies for realising building energy efficiency. According to Sharma (2013) there are over 50% energy saving potentials in building sector. As such, building sector should be considered as a potential sector to address the issues of global energy crisis and climate change. Besides, building worldwide is the main drive of the world economy and account for up to 40% of total energy use. According to Sharma (2013) the green building market in both the residential and non-residential sectors was estimated to have increased from $36bn in 2009 to $60bn by 2013 (Zhang and Cooke 2010). This shows that the market potential for green building is high and it is very important to implement sustainable passive strategies established in this study for residential building energy efficiency such as sustainable building envelopes, wall and roof passive strategies tested.

5.0 Conclusion

The findings derived from this study have proved that the utilization of insulation in residential building envelope, wall and roofing systems will significantly reduce heat transfer between the internal and ambient environment, thus reducing the energy demand of the structure and the relative carbon footprint of a structure per unit area over its lifetime. In addition, it has been proved that the utilization of a flat slab concrete roofing system as opposed to the roof sheeting alternative systems, will comparatively more cost effective for longer time and yield similar energy demand reductions. In the short terms, insulated galvanized and standing seam roofing systems are more energy efficient and cost effective, while in the longer terms, flat slab concrete roofing system is more energy efficient and cost effective. Also, this study concludes that the fibre glass fibre insulated masonry walls, roofs and envelope can reduce the energy consumption associated with thermal cooling making structures more energy efficient. The insulated envelope model, walls and roof system recorded the lowest relative humidity, indoor temperature values and hence performed the best in terms of energy consumption and thermal comfortability. In addition, the energy consumption values of the models tested showed that the fibre glass insulation utilised less energy to achieve thermal comfort. Hence, these results have showed that sustainable envelope, wall and roof passive strategies such as corrugated standing seam roof sheeting system with fibre glass insulation, corrugated galvanised roof sheeting system insulated with glass fibre, reinforced concrete flat slab roof, and insulated building envelope systems (Clay block wall insulated with fibre glass, corrugated standing seam sheet insulated with fibre glass, Terrazo floor finishing, and 100mm concrete slab) can be used to improve the energy efficiency of the residential building structures in hot dry climatic region. The implementation of these strategies is intended for low cost residential buildings in a hot dry climate.

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Energy Efficient Geometrical Design Parameters of Windows in Residential Building

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ABSTRACT

In the United States, 22% of the total primary energy consumes in residential building sector. In this sector, windows are responsible for 19% and 39% of heating and cooling loads respectively and 24% of the total building energy use in residential sector. In addition, since there is no limit for the glazing area in residential buildings, a careful attention in residential window design parameters would save significant amount of energy and subsequently reduces carbon footprint (International Residential Code, 2012).

Geometrical window design parameters such as window to wall ratio (w/w), aspect ratio, and fenestration location are among the most important design factors to improve building energy performance. Finding the most proper window design parameters is always challenging for the designers and should take serious consideration from the early stage of the design process.

In this study, an optimization model is developed to identify the optimum geometrical design parameters for windows. To achieve that, first, Simulated Annealing algorithm (local search algorithm) is applied and coupled with Energy Plus software. Then, a typical residential building is designed as a case study model in two different locations (hot and cold climates) to illustrate the application of the model. Finally, the result is analyzed and compared with the baseline model. The results show the amount of energy saved by optimum window design parameters and present recommendations for window designers in hot and cold climates.

Keywords: Residential buildings, Window design parameters, Simulation based optimization

INTRODUCTION

Energy consumption is increasing fast due to population and economic growth. In the United States, 22% of the total primary energy is used in residential building sector (US Department of Energy, 2012). This makes buildings responsible for almost 40% of CO_2, 54% of SO_2, and 17% of NO_X emitted in US (Asadi, 2014). Windows, as the eyes of the building, are the most vulnerable part of the building system from the energy point of view. According to Apte and Arasteh (2006) windows are responsible for 19% and 39% of heating and cooling loads respectively and 24% of the total residential building energy use. Since there is no limit in glazing area for residential buildings (Ching & Winkle, 2012), investigating the optimum glazing area would save significant amount of energy and subsequently reduces carbon footprint.

There are several window design parameters such as template and type of the glazing, window to wall ratio (WWR), reveal, dividers, shading, aspect ratio, airflow, control construction material, opening position, operational control, and fenestration location that impact on building energy consumption. Among those parameters, window to wall ratio (WWR) and aspect ratio are considered as geometrical design parameters which impact directly on the shape and size of window glazing and subsequently on building energy use (Foroughi & Asadi 2016).

In several studies (Vanhoutteghem et al. 2015, Amaral et al. 2016), which investigated the impact of window design on building energy use, have indicated that windows have to be carefully dimensioned for various orientations. A parametric study conducted to investigate the impact of window size, location, and orientation on lighting energy consumption (Acosta et al. 2016). It was concluded that horizontal windows for the case study model, located in London, UK, makes buildings more energy efficient (Acosta et al. 2016). According to Su and Zhang (2010), by selecting the right WWR for a building window in Shanghai, the total lifecycle environmental impact has reduced by 9-15%. Goia (2016) has investigated the optimum WWR for different climates. It is concluded that most of the ideal values are in a narrow range (0.30 < WWR < 0.45) while the WWR for south side window for very hot and cold climates is outside this range. The aspect ratio of south side window in Turkey is investigated by Inanici and Demirbilek (2000). The optimum aspect ratio for cold and hot climates are identified as 1:1.2 and 1:2 respectively. This shows a compact window is preferred for cold climate. The effect of geometrical factors on building window performance has studied by Susorova et al. (2013). It is concluded that selecting proper window design parameters improves building energy performance up to 14% in hot climate regions. While several researches have focused on the impact of single geometrical window design parameters on building energy use, a few have worked on multi design parameters and none of them has investigated the optimum geometrical parameters.

In this study, to find the optimum geometrical design parameters, including WWR ratio and aspect ratio, an optimization model is developed using Simulated Annealing (SA) algorithm. The developed program is coupled with EnergyPlus software to identify the optimum window design variables. A residential case study model is designed in Design Builder software to illustrate the application of the model and to identify the optimum design parameters for two various climate regions (Phoenix, AZ and Minneapolis, MN) in the United States.

METHODOLOGY

To identify the optimum window dimensions, a self-contained sequence of action (algorithm) should be applied in calculation process. Selecting suitable algorithm is crucial part in optimization process and it is depending on the type and numbers of variables and the nature of objective function. Since this study has a single objective function and the number of variables are limited, the problem consider as convex. Therefore, SA algorithm (a local search algorithm) is selected for developing the optimization model. Despite many other algorithms, SA algorithm, based on some specific conditions, does not ignore all of the negative results to avoid being stuck in local optima. Figure 1 shows the SA algorithm process.

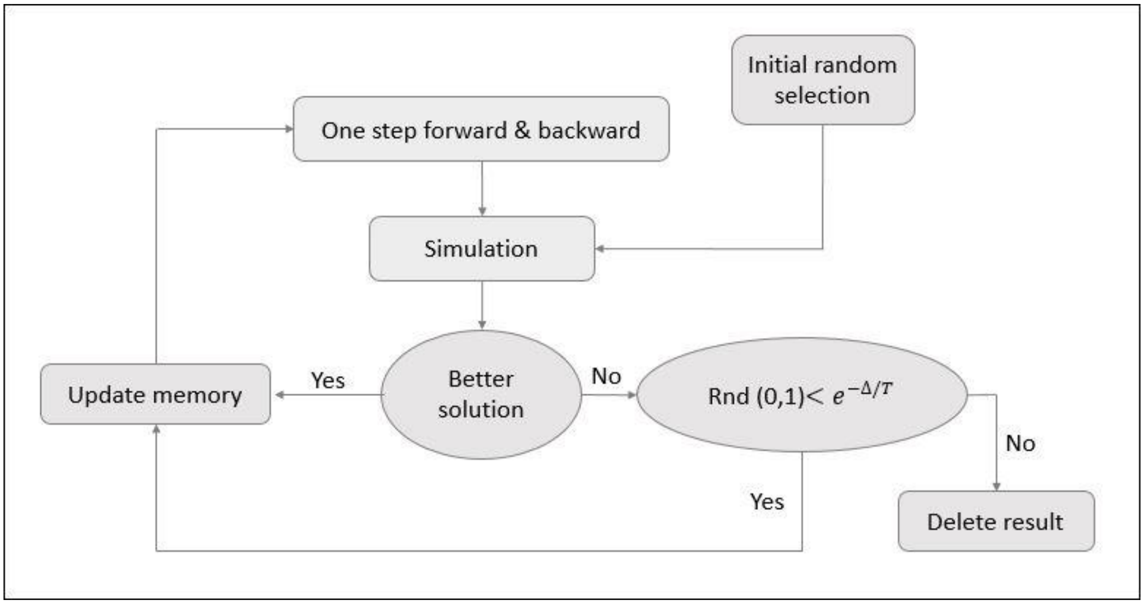

Figure 1. Simulated Annealing algorithm process

Design variables. In this study, two design variables including WWR (glazing area) and aspect ratio (the ratio of width to the height of the window), are investigated. In other word, the optimum dimension of window in each side of the building model is identified in order to minimize building energy consumption. To achieve that, four coordinates (four corners) for each window are considered as variables in the optimization model. Total number of 16 coordinates is listed in Table 1.

Table1. Variable Coordinates

Variables	Codes
Horizontal Movement of Northern Window	(nx1, nx2)
Horizontal Movement of Eastern Window	(ex1, ex2)
Horizontal Movement Southern Window	(sx1,sx2)
Horizontal Movement of Western Window	(wx1,wx2)
Vertical Movement of Northern Window	(nz1, nz2)
Vertical Movement of Eastern Window	(ez1, ez2)
Vertical Movement of Southern Window	(sz1, sz2)
Vertical Movement of Western Window	(wz1, wz2)

CASE STUDY

As it is shown in Figure 2, a single story pitched roof residential building is designed in Design Builder software. The building is a 12 (m) by 12 (m) cube with 4 meters height. The building has four windows, each is located in one side. The width and height of the windows are 6m and 3m respectively and the WWR is 37.5%.

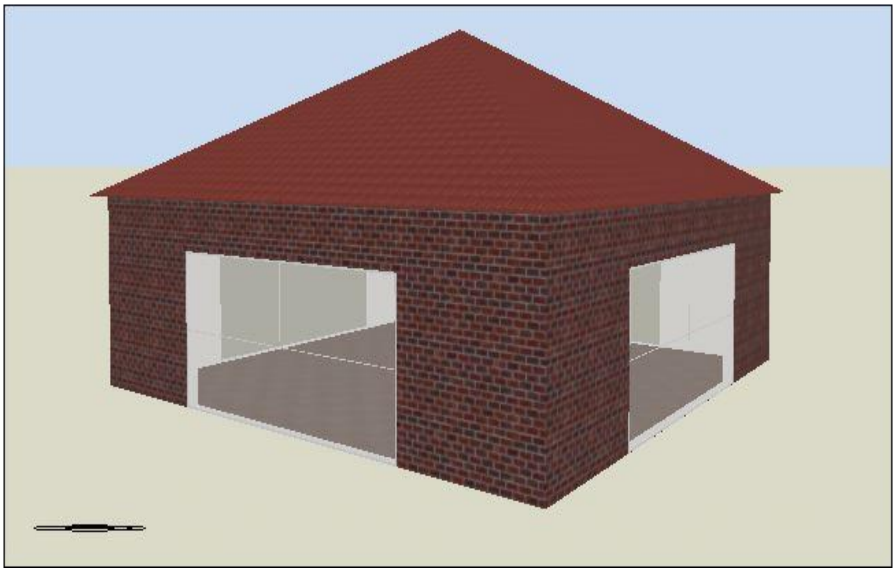

Figure 2. Residential case study model

A packaged DX is assigned for heating and cooling system with operating set point of 22^{o}C and 24^{o}C respectively. The external wall is made up of four layers including brick veneer, mineral wool insulation, concrete block, and plaster. The glazing system is considered to be double pane with 6 mm air gap in between and UPVC is selected for window frame. The construction material is listed in Table 2.

Table 2. Construction Material of the Case Study Model

	External Wall		Internal Wall		Window	
Layer	Name	Thickness (mm)	Name	Thickness (mm)	Name	Thickness (mm)
1	Brick	100	Gypsum	15	Glass	3
2	Mineral stone wool	50	Air Gap	70	Air Gap	6
3	Concrete block	100	Gypsum	15	Glass	3
4	Plaster (light weight)	13				

Climate zones. The case study model is located in two different climate zones (hot and cold) to compare the identified optimum design parameters. Phoenix, AZ from climate zone 2 and Minneapolis, MN from climate zone 7 are selected as hot and cold climate zones respectively. Table 3 shows the weather condition in these two climate zones.

Table 3. Studied Climate Zones

Location	Temperature range (ºC)	Humidity range (%)	Day length (Hours)
Phoenix, AZ	5.4-41.1	5-25	10-14.3
Minneapolis, MN	-16.2-28.9	22-104	8.8-15.5

RESULTS AND DISCUSSIONS

The developed optimization model has calculated the optimum window dimensions for more than 1500 times to achieve the minimum energy consumption of the case study model for each of the locations. The window dimensions of the minimum energy results are considered as optimum results and listed in Table 4. The longest width occurs in the north side window in Minneapolis, MN for almost 4 m long and the shortest, 90 cm, is in the south side in Phoenix, AZ.

Table 4. Optimum Window Dimensions in Cold and Hot Climate zones

	North width (m)	North height (m)	East Width (m)	East Height (m)	South width (m)	South height (m)	West width (m)	West height (m)
Minneapolis	3.95	1.9	2.00	2.29	3	1.06	4.30	1.53
Phoenix	3.34	1.5	3.55	0.43	0.90	0.65	3.63	1.45

As it can be seen in Table 5, the optimum glazing area, WWR, and aspect ratio are calculated from the optimum dimensions. In Minneapolis, (i.e., cold climate) the largest glazing area and consequently largest WWR occur in the north side window, around 7.5 m and 15% respectively, and the shortest is 3.18 and 6% in the south side window. It means, in this region to achieve the minimum energy use, in north side windows the optimum WWR should be 15% with the aspect ratio of 2, while in the south side the WWR should be reduced to 6% with aspect ratio of almost 3. Interestingly, the optimum results show that for the east side window, the aspect ratio is 0.9, which means the window should be installed vertically in order to minimize building energy consumption.

In Phoenix, Az (i.e., hot climate) the smallest glazing area occur in the south side of the building, 90 cm by 65 cm, while the largest occur in North and West with the WWR of 10%. Therefore, less or no window area is recommended in the south side of the residential building to prevent excessive light rays. In this region the aspect ratio of 2.2 is recommended for all sides except south side which is around 1.4.

Table 5. Optimum Glazing Area, Window to Wall Ratio, and Aspect Ratio

	North GA	North WWR	North AR	East GA	East WWR	East AR	South GA	South WWR	South AR	West GA	West WWR	West AR
Minneapolis	7.5	15%	2	4.6	10%	0.9	3.18	6%	2.8	6.6	14%	2.8
Phoenix	5	10%	2.2	1.5	3%	2.35	0.60	1%	1.4	4.9	10%	2.3

The optimum energy results in studied climate zones are compared in Figure 3. As it was predicted, heating loads in Minneapolis and cooling load in Phoenix are the highest. The lighting energy use is slightly higher in Minneapolis, around 300 kWh, and the total energy consumption in Phoenix is much less than total energy use in Minneapolis around 4000 kWh per year.

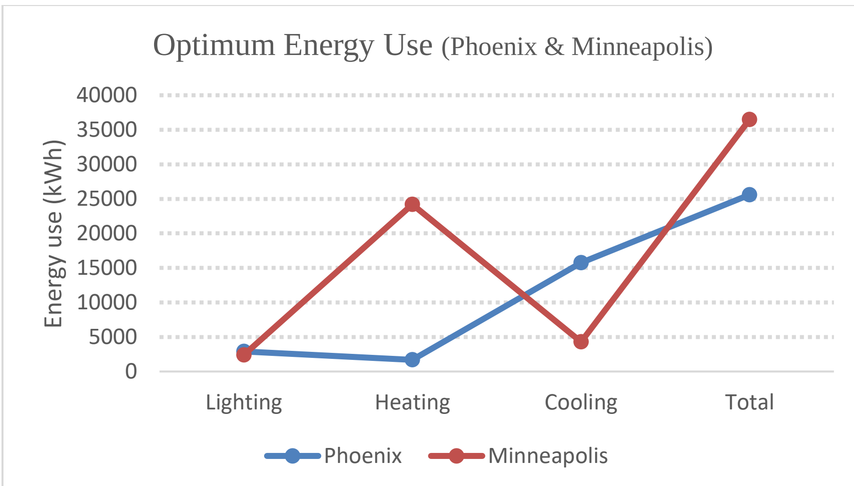

Figure 3. Optimum energy use (Phoenix vs Minneapolis)

As it is shown in Table 6, in Phoenix, identifying the optimum window dimensions have reduced the total building energy consumption significantly for 12,742 kWh per year, around 33%. The lighting and heating are slightly increased while cooling load is reduced significantly in compare with baseline energy model.

Table 6. Optimum Energy Use in Phoenix, AZ

Phoenix, AZ	Lighting	Heating	Cooling	Total
Baseline	1485	606	30115	38341
Optimum	2882	1683	15732	25599

In Minneapolis, as it is can be seen in Table 7, the total energy use has reduced for 5847 kWh, around 13% and almost half of the energy reduction in Phoenix, which means the optimum window dimensions are more effective in hot climates. The heating loads did not change, but lighting is slightly increased and cooling is reduced significantly in compare with the baseline model.

Table 7. Building energy comparison in Minneapolis

Minneapolis, MN	Lighting	Heating	Cooling	Total
Baseline	1706	24092	10417	42350
Optimum	2405	24167	4269	36503

Figure 4 shows the energy use comparison between baseline and optimum model in various sub meters including heating, cooling, lighting, and total energy use for two climate regions. As it is shown, cooling loads in both climates are reduced in comparison with the baseline model by identifying optimum window dimensions, while heating loads do not change significantly. Although total energy consumption is significantly improved in both locations, but the result shows more improvement in Phoenix, AZ (i.e., hot climate zone), which means optimum window dimensions have more impact on residential buildings in hot climate than cold climates.

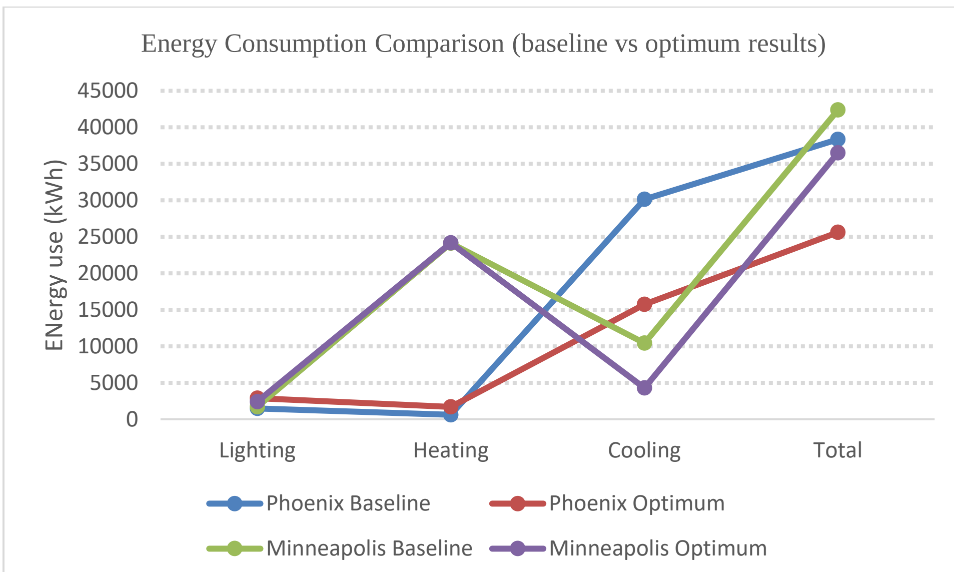

Figure 4. Energy consumption comparison

CONCLUSION

Energy consumed in residential building sector is more than 1/5 of total primary energy in US. In addition, windows in residential buildings are responsible for almost 40% of cooling loads. Since light rays can pass through windows more easily than the other parts, a careful consideration should take place in this section of the buildings. Window dimensions are crucial in order to control the energy use specially to make balance between heating and cooling loads, and lighting energy use. Identifying the optimum window dimensions would save significant amount of energy since it defines the optimum glazing size based on the sun angle and weather condition.

In this study, to find the optimum window dimensions, an optimization model is developed using Simulated Annealing algorithm. The developed model is coupled with EnergyPlus software, using Microsoft Visual Studio, to identify the optimum geometrical window design parameters including aspect ratio, glazing area, and window to wall ratio. To illustrate the application of the model, a single story residential building is designed in Design Builder software and its energy performance is investigated in hot (Phoenix, AZ) and cold (Minneapolis, MN) climate zones.

The optimization model has run for more than 1500 times to identify the optimum window dimensions. According to the results, the smallest aspect ratio, 0.9, occur in the east side of the building located in Minneapolis. This means the window should be installed vertically in order to minimize building energy use. The smallest WWR, 1%, occur in the south side of the building located in Phoenix, AZ. The results show in both cold and hot climate regions, the total building energy consumption has reduced by 13% and 33% respectively. In addition, since the optimum window design parameters reduce cooling loads significantly, it can be concluded that optimum window dimensions are more effective in the buildings located in hot climate regions. These results would help architects and engineers to improve residential building efficiency from the early stage of design.

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Housing Technology and the Contemporary Policy Context in the U.S

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Abstract

A handful of monographs and program reviews shed light on the basic missions and outcomes of past federal efforts to promote housing innovation. Few of these, however, describe the industrial and policy contexts in which those efforts emerged. Even fewer delve into the programmatic operations and components—or, the policy "ingredients"—of past and current housing research and development initiatives. In this paper, the authors review the evolution of housing R&D programs since the RAND report across these two themes: 1) the policy and industrial contexts in which the programs developed; and 2) the operational makeup of the programs. The authors trace these themes across public housing technology R&D policies and programs over the last half-century. In addition to reviewing the scholarly and policy literature, the authors conducted in-depth, structured interviews with staff of current and past federal housing innovation programs. In exploring the details of the programs, the paper describes how these two themes are fundamental determinants of program success—and, in some cases, failings—and should be included as decision-making factors for future efforts.

Introduction

RAND (Hassell et al. 2003) provided a useful history of federal R&D investments in general, along with descriptions of relevant housing-specific R&D efforts. Within the former, the report notes the parallel motivations of national security and economic competitiveness as being early drivers of the public sector's involvement in R&D during the post-war era, followed in later decades by the need to address threats to industrial productivity, demographic changes, and longer-term wellbeing across a variety of social, economic, and environmental areas.

Further, as RAND notes, three major trends have marked the landscape of R&D in housing: 1) the move to integrate public and private efforts more intimately; 2) the "broadening interpretation" of housing technology from direct structural engineering applications on the construction site (such as prefabricated housing components) to manufacturing, information, energy, environmental quality and a variety of other production and physical performance fields; and 3) the move towards thinking of the house as a "system," and consequent investment in comprehensive suites of technologies or technology performance areas rather than individual discrete processes and products. This synergy, however, did not always exist in the field of housing technology, nor did it play it out uniformly between different governmental entities and industry counterparts.

Written at a time when multiple housing R&D programs flourished, RAND (2003) argued that the evolution of public R&D investment had been for the better. Yet, it is unclear why and how these programs successfully came to be, and whether their perceived success was due as much to the policy conditions and industrial context at the time as to the programs' effectiveness. What policy and industrial conditions must exist for the creation of housing R&D programs? Which program components are primary determinants of a program's durability? And, to the contemporary situation, can a program succeed when these conditions and workings are not present?

Past and Current Housing Innovation Programs

A fundamental belief in the capacity of scientific, engineering, and related disciplinary research to provide societal returns in exchange for the public-sector investment—and private returns to business investment—runs throughout the modern American era. When Vannevar Bush first proposed institutionalizing a national R&D policy and creating what would become the National Science Foundation after the Second World War, there had been a few, fragmented applied research programs within the federal government whose resulting products were primarily for government uses (Zachary 1997). Bush valued the significance of applied research and development enough to note that one function of national policy would be "to devise and promote the use of methods of improving the transition between research and its practical application in industry" (Bush 1945).

Yet, the depth of the belief in publicly-supported R&D has varied significantly over time based on policy conditions and the state of the housing industry. In turn, how that belief manifests into operational and effective public-sector R&D programs or private-sector laboratories and commercialization efforts also fluctuates. For example, the early implementation of Bush's new national policy focused on basic research alone, with an added focus on tax and patent policy to ensure that industry could commercialize new knowledge. It would be over several decades before the political and business worlds would align and a concerted effort to support applied research—and the housing industry in particular—would emerge.

Various federal agencies had adopted housing R&D pipeline programs of some form and relevant to their respective missions at the time of the RAND report. Notable public-sector housing design, construction, and technology R&D programs have been created in many governmental institutions. There have been ongoing public programs for general research that have, on occasion, included housing applications such as USDA's Cooperative Research and Extension Services, NIST's Advanced Technology Program, the NSF's and DOE's Established Program to Stimulate Competitive Research, NSF's Industry-University Cooperative Research Centers and Engineering Research Centers, and individual public university research centers' collaborations with industry.

At peak levels in the late 1990s, federal funding for R&D and related commercialization activities for housing technological innovations averaged over $200 million annually—a sizable investment though still less than 1 percent of the national non-defense R&D budget. RAND (2003) reviewed two historical and four contemporary housing R&D programs in the federal government. Others (Martín 2015) have supplemented these reviews with more detailed documentation of authorizations, appropriations, and internal reviews of these and a handful of other programs. Below, we update these reviews while placing the programs in their policy and industrial contexts to better understand the relationship between contexts and program outcomes.

Civilian Industrial Technology Program (1962)

The first R&D program to that would address housing technology was proposed in 1962, as part of a larger cross-sector commercialization program proposed by President Kennedy's economic advisors to increase economic productivity in the industries "without any organized stimulus to change." Though never implemented, the Civilian Industrial Technology Program (CITP) anticipated supporting both applied research at universities as well as information and dissemination activities to local industries and stakeholders, like the Cooperative Extension program, but across numerous sectors.

The construction industry was targeted as one sector early on, though the residential construction industry was neither experiencing extreme growth or contraction at the time. CITP's policy argument was largely based on the potential economic gains from any public R&D investment regardless of sector and sector conditions at the time. The case for public intervention was further strained when improvements in the costs, delivery time, or quality of new housing were not apparently needed—at least according to industry leaders. Ultimately, the CITP was never authorized as a formal program that included the construction industry (Nelkin 1971).

Two reasons have been suggested for the CITP proponents' failure. First, there were fundamental concerns regarding public funding for the later stages of civilian technology innovation as a substitute or even complement for private-sector funding. This difference in policy philosophy around the role of government had not been aired during the post-war military-industrial R&D buildup, though those investments were made explicitly to create new technologies for defense and space exploration purposes (even if there were technology spin-offs from these investments that were subsequently commercialized). In contrast, CITP's stated purpose was to work on the specific industry's technology development, commercialization, and adoption rates for general consumer benefit. As the first effort proposed by the federal government to focus exclusively on applied research, CITP suffered from the lack of resolution to the debate over that kind of broad investment since Bush's seminal report.

Ironically, it was the construction industry itself that lobbied against the CITP, partially because the program would infringe on industrial affairs and free markets (Teich 1986). As the second and more political reason for CITP's demise, the builders based their opposition on the grounds that other policy challenges beyond technological innovation were more pressing (such as increasing regulations). Product manufacturers were also fearful that federal research products could compete with theirs, since CITP had no provision for public-private research partnerships. Without the buy-in of industrial partners, then, CITP was doomed. If housing technology is an area of applied research, industry (the stakeholders who "apply" it) must be involved in the creation and articulation of R&D programs.

Because CITP for housing was never authorized or implemented in any way, the only operational lesson is the role of early and robust partnerships in establishing effective programs given CITP's oversight in understanding the motivations of industry stakeholders. A related contextual lesson from CITP comes from its proponents' disengagement with these stakeholders: CITP had no clear industrial or societal motive for institutionalizing an R&D program beyond general economic productivity. CITP could not articulate a compelling vision for innovation to the very industry it intended to innovate.

Operation Breakthrough (1968)

A few years later and after the formal establishment of HUD, Operation Breakthrough built off the operational lessons from CITP while presenting a more compelling policy justification for the federal government's investment in housing research (Martín 2015). Breakthrough also was seeded at a unique moment in the housing market cycle: when the program was first proposed in 1968, the housing industry reached a peak in both production and the home values. Production constraints provided necessary reasoning for technological investments, but Breakthrough was also designed with an eye to providing societal benefits from "mass housing" of up to 10 million new units—a goal aligned with concerns surfaced in the national discussion about urban housing through the Douglas Commission.

The combination of industrial capacity to take on R&D partnerships given its record revenues with the societal mission presented in the form mass housing cemented the opportunity. Though the Johnson administration had presented the goals and focus for a housing R&D program and appropriated funds to that end, its design and operations were left for the next administration. The Nixon administration, however, proved to be broadly supportive of applied research—a fact that would be confirmed in its 1971 proposal for a New Technologies Opportunities program (Block and Keller 2011). Operation Breakthrough was fully funded at its 1969 start and with active involvement and design by HUD leadership under Secretary George Romney.

Where CITP failed to partner with industry, Operation Breakthrough foregrounded two mechanisms for a mutually satisfying relationship. The first involved convincing an industry that had been suspicious of governmental meddling only a few years before to support an R&D program. Breakthrough's proponents articulated a set of R&D activities that intervened at all points of the innovation pipeline and not just direct research funding. Operation Breakthrough proposed to address the barriers to housing innovation, but also the numerous bottlenecks for overall productivity in the housing industry: the program encouraged "new technology, improving architectural design, using the full range of labor skills, [and] overcoming building code, zoning and labor constraints" (HUD 1970). R&D would be a means to an end that the housing industry could support.

A second tactic was the direct involvement of organizations from the building industry via public procurement. Teams of construction firms and engineers bid to develop and demonstrate new large-scale housing system prototypes that would be used on new HUD-owned housing. These systems would incorporate all aspects of the design and construction process, including zoning assessments, multiple-use designs, streamlined mass-produced building materials, and expedited construction methods. Direct financial incentives for participating in Operation Breakthrough complemented the intrinsic benefits to the industry from partnering with the public-sector to improve innovation rates and production bottlenecks.

However, the same strategies that were used to justify Operation Breakthrough's creation would become the program's downfall. Breakthrough bit off more from the private sector than it could chew in the public. Attempts to address all challenges to housing production while grappling with the R&D pipeline proved to be too overwhelming, even for the substantial funding that HUD was appropriated in the program's duration (about $72 million). As a 1976 RAND report suggested, this approach to R&D was "several orders of magnitude more complex than simply funding R&D projects" (Baer 1976). That complexity was far more than the program's resources and leadership—which was steered by former auto industry executive Romney—could absorb.

Breakthrough provides other key operational lessons beyond appropriateness of resources to mission. HUD had virtually created laboratory conditions for the innovations it supported by creating an artificial demand for housing innovations outside of the commercial market. Though technological spillover from public-sector investments was common in other industries, there simply was not enough consumer or industry demand for Breakthrough's technologies during its run. Further, the waivers that HUD enforced were essentially loopholes from the traditional state and local building regulations. These waivers became another structure in Breakthrough's Potemkin village, despite HUD's attempts at monitoring innovation constraints (HUD 1970). By creating an artificial R&D pipeline parallel to the industry's reality, Breakthrough ultimately "did not create the large, continuous markets necessary for efficient industrialized housing construction" (GAO 1976). Combined with a major industry downturn in 1973, perceived failures in the program's short-term results led to the program closeout the next year.

In short, Breakthrough's lessons for future housing R&D programs involved: 1) accurately and regularly assess market demand in light of different housing markets and fluctuating cycles; 2) designing an appropriate number of activities that could be feasibly undertaken within the desired policy timeframe and appropriated budget; 3) coordinating the activities in partnership with industry and other stakeholders in the areas in which the research would be applied; but also 4) operationalizing that partnership within the actual supply chain and its labor, material, and regulatory constraints.

DOE Energy Policy and Conservation Act programs (1975) & Office of Conservation and Renewable Energy (1981)

Many of the assessments of Operation Breakthrough were conducted at a time when other agencies in the federal government were considering their own versions of housing R&D and demonstration programs. After Nixon's warning of an impending energy crisis due to the first OPEC embargo in 1973, the Energy Research and Development Administration was created under President Ford's 1974 Energy Reorganization Act. The new unit within the then Federal Energy Administration was charged with consolidating all energy-related research projects, including those focused on renewable energy sources and possible energy conservation techniques (Fehner and Holl, 1994). These remained relatively limited, and a handful of states created their own policy and research agencies such as the New York State Energy and Research Development Authority and the California Energy Commission.

Both the crisis and substantial national research investments in the building sector's energy use did not fully materialize in the federal government until Carter's 1977 declaration of a national energy emergency as the “moral equivalent to war.” The Department of Energy established that same year further consolidated all federal energy-related research into one agency, but established a structure for the staff and resources by according to stage along the R&D pipeline rather than by energy source or use: specifically, the Office of Energy Research coordinated basic scientific projects, the Office of Energy Technology led applied research, and the Offices of Resource Applications or Conservation and Solar Applications focused on commercialization. The national energy laboratories were also integrated into the consolidated department.

Early building-related research was limited, though solar renewable research projects received significant funding. By 1979, the peak year of the Oil Crisis, the administration began expanding R&D efforts to focus on consumer demand concerns with proposals for a loan bank for residential solar units and residential solar tax credits. Though clearly different from the housing need from a decade before, an urgent societal need for investing in energy-related R&D with potential housing applications was articulated. The housing industry had also recovered from its Breakthrough-era contraction at this point, though the new energy R&D proponents had not articulated a role for them as much as for renewable energy providers.

In the midst of the crisis, the Department was reorganized again to better address sector-specific needs, including a distinct energy conservation office which would later become the Office of Conservation and Renewable Energy under the Reagan administration. Under new leadership, the R&D focus shifted from applied research and commercialization to basic research "only in areas where these market forces are not likely to bring about desirable new energy technologies and practices within a reasonable amount of time is there a potential need for federal involvement," as designated by the new Energy Secretary Edwards in 1981 who also sought to dismantle the Department in general.

With continued bipartisan Congressional support for R&D funding in general, however, the administration moderated its cuts to focus on industry education (“technology transfer”) and consumer awareness campaigns in addition to basic research while steering clear from applied research and commercialization. The Department described energy conservation and efficiency efforts as one of the “energy triad” of resources (along with coal and nuclear energy) to be further tapped, and continued a minimal funding stream to these technology transfer efforts though without explicit support from the housing industry. Appliance standards were the primary housing-related focus of these conservation efforts. Though modest, the development of energy efficiency standards persisted as both operationally manageable and politically acceptable efforts. By the mid-1980s, the housing market had once again turned downwards and, combined with decreasing prices for energy, the appetite for other housing research had waned for the time being.

DOE Advanced Housing Technology Program (1991); Office of Energy Efficiency & Renewable Energy (1993); Building America (1995)

President Bush announced the development of a new national energy policy early in his administration, and held hearings throughout 1989 and 1990, eventually reporting that the “loudest single message was to increase energy efficiency in every sector” (DOE 1990). Combined with energy price shocks from the Gulf War, these comments led to modest but notable attention to residential energy efficiency R&D and related commercialization efforts in the eventual energy policy report released in 1991 that led to the 1992 Energy Policy Act. The Act increased regulatory requirements across numerous industries, while incentivizing new R&D. With the housing market heating up once again, the Department under the Bush administration supplemented its appliance efficiency and consumer awareness campaigns with additional funding increases for the conservation office every year through 1993.

New funds were used to set up additional residential construction energy efficiency pilots and demonstrations with private-sector partners and the national laboratories, including seed funding for the Advanced Housing Technology Program (AHTP), modeled after the National Institute of Standard and Technology's Advanced Technology Program, launched in 1991. Though only a component of the Department's broader energy-efficiency portfolio that eventually merged into others because of the change in administration, the program attempted to pick up where Breakthrough left off with regards to comprehensive assessments of the industry's innovation rate but learned from that program's lessons regarding trying to address too many of the industry's other productivity challenges as well. AHTP planted the seed for what would become a broad set of programs across the federal agencies

The Clinton administration's push to fund a wide range of R&D programs centered especially on energy efficiency efforts given the new policy beliefs in societal benefits from integrating reductions in energy use and environmental impacts with economic growth. Applied housing research was an ideal site for this given both the sector's size (which, by the early- and mid-1990s, was formidable and ever-growing) and the industry's potential for significant gains in energy efficiency with relatively small but pervasive technological changes.

The newly renamed Office of Energy Efficiency and Renewable Energy cast a wide net in its programming, tying the Department's previous energy efficiency R&D and commercialization work to the administration's new Climate Change Action Plan through the pursuit of voluntary public-private partnerships. By 1994, the budget for energy efficiency applied R&D, technology transfer, commercialization, and awareness programs in general increased dramatically. The number of Cooperative Research and Development Agreements (CRADAs) between the federal government, industry, and university researchers doubled, for example.

The emphasis on the stages in the innovation pipeline from applied research on began to equal the traditional emphasis on basic research in the Department and the federal government overall. Centerpieces of this work have been the Building America program (the development and demonstration partnership with procured housing consultants and builders), technical assistance to the ENERGY STAR for Homes program (the certification and awareness campaign program), and simulation, evidence-building, and advocacy in the Building Energy Codes Program. These three programs were designed to serve as federal interventions along the full length of the housing innovation pipeline.

In contrast to previous housing technology programs, these Department of Energy activities were created at a time when the industry was recovering from a modest contraction—though that recovery yielded increasing production and growth for the industry for over a decade to come. Industry support resulted from the immediate returns to consultants, energy raters, and builders who participated in Building America teams, the competitive advantage of marketing energy-efficient homes, and in the operational preparation for likely regulatory changes. Policy support for these public-private partnerships in housing R&D persisted even during subsequent administration transitions in 2000, and supplementary programs such as the Zero Energy Home program and demonstrations of water management and indoor air quality technologies were all added over the next few years.

EPA ENERGY STAR for HOMES (1995)

Building off its successful appliance and electronic product labeling program, the Environmental Protection Agency (EPA) launched the ENERGY STAR for New Homes program in October 1995. Housed within its climate change response programs, ENERGY STAR for New Homes was designed as a voluntary energy-performance certification and label relying on proven design, materials, and construction techniques. In many cases, though, the performance criteria became standards for national housing programs late in the 1990s and were adopted into state and local building codes. Because of the proliferation of energy regulations meeting the originally voluntary performance criteria set by the program, ENERGY STAR revised them in 2006—a year of near-record housing unit construction and home prices in the U.S. Like its DOE program counterparts, ENERGY STAR also expanded to include programs addressing other EPA goals, such as water conservation and indoor environmental quality improvements.

ENERGY STAR for Homes was the most successful of the housing technology programs coming out of the 1990s as measured by the number of housing units directly affected (tested and labeled)—a testament to the effectiveness of voluntary partnerships in meeting both the productivity gains desired by industry and the public sector's societal goals. The program's known capacity to leverage modest public funding with industry marketing and promotional resources provides an operational lesson about the appropriate sizing of public sector efforts, in addition to the highlighting the potential of market demand as an influence on housing R&D rates.

HUD Partnership for Advancing Technology in Housing (1998)

The operational lessons regarding collaboration with industry within housing R&D were not taken on solely by the energy and environmental departments in the 1990s. The same year that the Department of Energy proposed the Building America program, the Subcommittee on Construction and Building in the National Science and Technology Council's Committee on Civilian Industrial Technology set forth a plan to collaborate with the private sector to develop a comprehensive national R&D policy (NSTC 1994). The original plan covered the entire construction industry and focused solely on the benefits to construction productivity and workforce safety. One year later, the plan expanded to include a broad set of ambitious goals for performance improvement in U.S. housing, such as a 30% reduction in "first costs" for residential construction (NIST 1995; NAHBRC 1998) which, in turn, expanded to an even wider and more aggressive set of goals when the Partnership for Advancing Technology in Housing was proposed in 1998 by the Clinton administration with robust and explicit industry support.

PATH was housed as a separate office managed under HUD's Office of Policy Development and Research. The proposed goals for improving both industry innovation rates and simultaneous housing and housing industry performance were immediately identified as too broad and insurmountable for a program allotted such modest resources and charged with coordination across numerous public- and private-sector partners (NRC 2003, 2006). In the aftermath of the 2000 presidential election, the program's administration reverted to PDR& staff. The goals were also restructured to follow along the housing innovation pipeline without preference to any specific housing performance area (e.g., energy efficiency or durability) for new single-family housing (PATH 2005). Continued industry support and advocacy on the program's behalf supplanted administrative support for the program, resulting in diminishing appropriations until the program was terminated in 2009.

PATH, then, was ultimately the least sustainable among the suite of federal housing R&D programs coming out of the 1990s. Though it implemented several of the fundamental policy lessons learned from the previous programs and existed at a time of growing industrial capacity, it failed to articulate a compelling societal need that could translate into a political catalyst for support. Combined with the massive downturn in the single-family housing sector in 2008, the policy and industrial conditions under which PATH was justified no longer existed.

DOE Better Buildings (2010)

In contrast, the various DOE residential R&D programs received a boost in the aftermath of the housing market crash. This expansion came on two fronts. First, the infusion of massive resources from the 2009 American Relief and Recovery Act provided DOE with resources to expand many core technology tools and research efforts (such as home energy scoring tools) under new efforts like the Better Buildings initiatives, which included the Neighborhoods Program's vast state and local energy block grants and the Residential Network of housing and energy-efficiency service providers, the colossal expansion of existing energy programs like the Weatherization Assistance Program, and a host of other market-supporting efforts that secured an ongoing demand for current and future energy-efficient innovations in the housing sector. These efforts were particularly focused on existing homes—the sole growth area in the depressed industry and the focus of broader national recovery goals.

Despite the downturn in the housing market, the administration made the policy case via executive initiatives such as the Vice President's "Retrofit Ramp-Up" that continuing—and dramatically expanding—federal support for housing R&D and related housing innovation pipeline programs was needed to respond to the merging national emergencies of an underemployed workforce, persistent energy and environmental impacts, and a markedly altered housing industry. Support from other industrial sectors, such as energy-efficiency service providers and remodelers, buoyed this effort. Viewed against past housing R&D programs, the post-recession DOE residential programs broke the pattern of industry support for federal intervention only during times of growth and peak production.

Second, DOE restructured its EERE operations to better align its historical R&D and demonstration programs like the Emerging Technologies and Building America programs, with its demonstration and commercialization programs such as the Zero Energy Homes, the Solar Decathlon, Home Performance with Energy Star, etc., and, in turn, with the marketing and regulatory pull of its building code advocacy, ENERGY STAR (with EPA), and the new ARRA-funded assistance programs. Further, these programs pivoted from their previous focus on technological change in new single-family housing construction to the remodeling and multi-family housing sectors more flexibly (DOE 2015).

This new "Residential Building Integration," as the new operations were titled, involved a consistent alignment of activity specifications and performance requirements across the scope of residential energy R&D programs. Beginning in 2010, DOE envisioned the effort as an opportunity to "road-test building science measures targeted for the next new homes specification" while providing an opportunity to "promulgate technologies and best practices successfully established in their Building America research program" (EPA 2010). Taking this iteration of operations as the latest stage in a continuum of programs and activities, then, the DOE residential energy efficiency programs have collectively been the longest-running housing R&D program in federal history and the most comprehensive regarding the number of touches along the industry's innovation pipeline.

Context

In the review of past and contemporary programs, patterns emerge about the context in which applied research is conceptually justified and realistically developed as a vehicle for public intervention. Three core patterns emerge:

- Underscoring all contextual conditions is an underlying philosophical tension around funding industrial research with public-sector resources. Conflicting economic, policy, and political reasoning has been put forth, but the record suggests that the ***philosophical arguments for federal intervention being warranted and even desirable have been successful*** on the whole;
- The policy context—that is, the social, economic, and political circumstances in which the need and development of rules, regulations, laws, and resource allocations are made—has also widely varied since the first housing R&D interventions was proposed. Yet, the timing in which this philosophical pattern has manifested in actual housing R&D programs over the past half-century is the most revealing trait. ***These moments have typically been marked by a pressing national emergency or perceived societal benefit***. The articulation of this urgency by policymakers has served the dual purpose of framing the goals and activities of the program, but also presenting a rallying cry for industry participation and consumer demand. This trait has especially marked the programs that are either particularly impactful in terms of U.S. housing quality changes or successfully sustained over time and administrative transitions.
- A pattern is also detectable across the fluctuating industry characteristics and market dynamics over this time. ***The industrial context in which R&D programs were successfully launched tended to be marked by growth in production***. Whether on the upswing after a contraction or near the peak of the housing production cycle, stakeholders tended to call for R&D investment in both industry and public-sector only when they noted the industry had the financial and knowledge resources to participate. In contrast to other industries in which the appropriation of R&D resources has been central to their organizations' business models or to their strategies in retrenchment, resources for R&D among housing stakeholders were typically allocated as distinct from regular operations—hence, the research

investments in market upswings. Exceptions to this pattern come primarily from regulatory mandates that require changes in industry products or to production processes.

These three patterns are explored below.

Philosophies on federal applied research

With only two exceptions in recent history, there has generally been bipartisan support for government resources being used for applied research purposes, and specifically for housing R&D, since the establishment of scientific and engineering research policy in the post-ware era. The first program reviewed above and the only one to have not launched because of stated ideological differences sheds some light on these arguments: CITP. Supporters argued that, at a fundamental level, the industry was an innovative laggard and technological obsolete, that technology transfer in construction was necessary for broader economic development and to satisfy pressing social housing needs, and that public funding was needed as a consequence. Opponents, however, argued that the industry was already productive and sound, that innovation in housing occurred and societal needs could be met based on free markets, and that applied R&D programs (as opposed to other construction sectors for which the public-sector is a consumer, like infrastructure or public works) would threaten the balance between public and private sectors. The creation of CITP, arguably, would overextend the federal role.

The success of CITP's opponents was short-lived given Operation Breakthrough's highly publicized launch. Beyond CITP and the reductions in energy-efficiency and renewable energy research in DOE in the early Reagan years, however, support for investments in housing innovation have largely been bipartisan. Even Operation Breakthrough, signed into creation by a Democratic administration and Congress, was enthusiastically implemented under a Republican one. One potential explanation for this evolution has been the increased economic justification for public-sector R&D intervention. As early as the 1950s, Vannevar Bush noted "the benefits of basic research do not reach all industries equally or at the same speed." However, the fundamental disagreement about the public involvement in free markets and their stakeholders' innovation pipeline persisted (NRC 1986).

One argument in favor of supporting housing R&D is that the government has a substantial procurement interest in the eventual product (Nelson and Langlois 1983). Proponents of Operation Breakthrough and PATH often noted the budget significance of federal housing assistance (particularly public housing) and military housing as a fundamental justification for investments in cost-saving and performance-enhancing housing technologies. However, as direct control over the physical construction and maintenance of these housing sectors has waned over time (such as through HUD's Rental Assistance Demonstration) this argument has become salient.

Advanced economic exploration of the broader societal benefits from investment came in the early 1990s; common market failures such as gaps in public information about housing quality, the asymmetries in information access between producers and consumers of housing innovations, and the externalities arising from when the housing industry is too fragmented and no single player can take on the burden of innovation have all served as fundamental defenses for public decisions to venture into housing R&D (Romer 1990; Jaffe 1996; Martín

2006). Peer reviews of building industry R&D investments at the same time confirmed these barriers and the need for public investment to overcome them (NRC 1992a), presciently foreseeing the growth of programs later that decade.

Over time, then, the fundamental argument over whether there is a public role in housing R&D has been substituted by differences over the form and substance of that role. The core policy decisions now center on the appropriate balance in activities between basic research, applied research, and commercialization activities, and between direct public funding of research versus creating financial and other incentives for industry research. By 2007, for example, the federal non-defense R&D budget across all subject areas was evenly divided between applied and basic research efforts (CBO 2007).

The transition to the Trump administration presents a new chapter in this philosophical debate, with policy statements in early budget proposals taking a position against applied research. For example, a proposed cut to DOE's program funds "reflects an increased reliance on the private sector to fund later-stage research, development, and commercialization of energy technologies and focuses resources toward early-stage research and development" (OMB 2017).

Policy context

An early challenge presented to CITP was its inability to articulate a national goal and resulting program mission for its existence beyond the conceptual returns to the general economy from research investments in major industries. Several subsequent programs fell into similar traps either during their development stages or after only a few years of implementation, from Nixon's 1971 New Technologies Opportunities, to the demise of NIST's Advanced Technology Program (2005) and Technology Innovation Program (2012). PATH's 2008 termination can arguably be classified in this group too, since the program was unable to foment a broad industrial and policy constituency to support its revised goals. As Teich argues in a 1986 paper commissioned for the National Academy of Sciences, however, these failures were typical of programs that were "either aborted in their launch phase, or terminated before any real results could be seen. They were political failures, not technical failures."

The historical record suggests that the programs that articulated a clear and focused goal in relation to a pressing societal problem were more likely to be sustained in terms of financial and advocacy support, even when the expected societal returns to the public-sector investment are not realized for decades (when policymakers have changed and the causal links to the investment are blurry) or when the specific theory of change and consequent portfolio of activities were revised along the way. The problems in question, if urgent enough, then became the subject of policy interventions under the belief that investments in housing innovations could partially address the problem and result in other societal benefits. In the housing R&D world, the pattern of having compelling policy arguments did not start with the post-war creation of the university-industrial complex, but with the housing access issues in the 1960s followed by the 1970s' energy crisis.

The programs with any measure of success have also survived political transitions, suggesting that that the policy justification is compelling enough to overcome modest difference in political philosophies regarding the public-sector's role in applied research that are described earlier. As Noll and Cohen suggest in a 1985 paper commissioned for the National Academies, successful R&D efforts are those that are insulated—though not isolated—from changing administration priorities (Noll and Cohen 1986). In fact, ideologically motivated projects or political pressures based on geographical interests are reported causes of failure in R&D investments (Ahearne 1986). Politics, then, are not necessarily as significant a determinant of successful housing R&D efforts as policy.

A 1992 National Academies committee report suggested three dominant motives for public-sector involvement in new building technology and innovation: "1) to achieve an appropriate balance of cost, quality, and performance in government facilities; 2) to enhance quality of life in the United States generally… by encouraging better cost—initial or life cycle—quality, and performance in private sector building; and 3) to enhance the productivity and commercial success of U.S. construction-related industries in domestic and overseas markets" (NRC 1992a). Given the structure of the US housing market being predominately privately-owned (even when accounting for housing assistance) and the lack of foreign competition in local construction markets, only the second motive seems relevant for contemporary policymakers. The historical record corroborates the strength of this single policy motivation's contribution. The policy challenge, then, is in articulating an "enhanced quality of life" that addresses a societal problem *and* the needs of industry constituencies that stand to gain from the innovations.

Industrial context

Across the programs reviewed in this paper, a positive state of affairs in the housing market overall appears to play a significant role in defining industry needs for R&D. In almost every program case, the industry's production was either on the upswing or (as we can see with historical perspective) at peak levels in the market cycle. Some qualitative historical evidence suggests that economic fluctuations in the housing market partially determine the rate of innovation. This is somewhat supported by studies in economic theory, though actual empirical analyses seem sparse (Myers 2016; Bon 1989).

Highs and lows in housing markets dramatically shape the ability to invest in research and development, to provide information, education and training in the industry, and bring attention to the industry's innovation rates to the point of enacting industrial or governmental policy responses. The argument supporting this pattern is that, during market highs, the housing industry has the financial resources for innovation investment but there is no time for solely private-sector innovation investment and commercialization, and little incentive or advantage for a single stakeholder to take on the R&D investment because of high demand for the existing product. During market lows, not only does the reverse hold, but there is also no demand for innovation since there is no demand for housing.

In either case, there is little "demand pull" for innovations without an external policy-related prompt (like energy regulations, public health hazards, or housing affordability crises). "Supply push," however, could be a driver of housing innovation during both peaks and valleys when manufacturers and builders seek a competitive advantage. The question is whether the public-sector can time interventions to match the magnitude and direction of the industry's upwards swing in a cycle, and can structure the intervention's operations and activities to ride out the downturn.

Operations

The patterns across philosophical, policy, and industrial contexts noted above suggest opportunities for defining the timing and circumstances under which housing R&D support may be successful. However, a second set of programmatic questions regarding decisions and operational structure also play a critical role. In fact, some scholars speculate that "pragmatic criteria outweigh philosophical concerns in the final analysis, and the politics of research will be more constructive when those involved can focus on details of specific programs, including the industrial and policy environments in which they must operate" (NRC 1986).

Core operational determinants were explored in the policy literature and through interviews with contemporary federal staff charged with housing R&D program operations.

Leadership

As many have noted previously, housing R&D programs are among the research initiatives that must walk a political tightrope between near-term technical payoffs and the long-term innovation gaps in the industry. Yet this struggle is only realized after a program is launched. After a clear societal need is framed in policy terms as noted earlier, there must be a sustained commitment on the part of key policy leaders in either executive or legislative branches of government in support of the program's vision and operations. In short, a technological champion or group of champions is needed within government at the highest levels of authority just as champions are needed within the private sector's stakeholders (Nam and Tatum 1997).

In addition to the general policy support, this backing must be operational, including continual commitments for press events and policy announcements, general involvement in resource allocation and program structure, and interest in the program's outputs and outcomes. In past successful examples, this support always involved at least one of the government branches, typically involved multiple individual champions (for example, members of Congress and a cabinet-level executive), and were often bipartisan. In turn, the champions for successful programs were involved beyond ribbon-cutting but without approaching micromanagement.

Though not consistently observed, bipartisanship appears to be a particularly important factor for ensuring that political considerations are not considered when structuring the program and that technical, economic, and other evidence-based assessments are the primary determinants of program management, location of research, and interpretation of research findings. Bipartisanship also insulates (but does not isolate) the R&D program from political concerns and changes in political leadership. Political factors and special interest groups are never completely avoided, but program leadership's awareness of the positions and politics of champions or detractors can help mitigate them.

Partnerships

A second but just as significant operational pattern across successful housing R&D programs is the early and active involvement of partnerships, particularly with the housing industry sectors for whom the program is meant to benefit (e.g., window manufacturers, single-family home remodelers, energy retrofits etc.). Successful partnership not only benefit these industry stakeholders, but also build a natural constituency to advocate for the public-sector efforts. The importance of industry partnerships was the first lesson taken from CITP, and it was a lesson that was consistently employed by all programs (successful and otherwise) since, that has been affirmed in numerous studies (NRC 1992b and 2003), and that was described as an essential program ingredient by all interview respondents. The balance of this program's advocacy between the partners should be appropriate to the expected benefits—meaning that the industry partners must have a vision for the future of their industry that includes technological change as much as the public-sector and research community does.

The timing, project content, division of labor, cost-sharing, and representativeness of partnerships were identified as critical components for ensuring that a public-sector housing R&D program is appropriate to the specific industry or sectors it will serve.

- Regarding ***timing***, early collaboration in project initiation and design were critical, even before launch. This ensures that the industry can articulate its R&D challenges and inscribe them into the program activities well, but also that mutually beneficial roles are established early on.
- Partnerships should also identify specific program or ***project content*** areas or activities that are relevant to industry but justify public intervention. Examples of this kind of content development and negotiation came in the manufacturing sector agreements with EPA and DOE for appliances and lighting, and in the "technology roadmap" process established in the 1990s' programs.
- The ***division of labor*** must also be critically defined to specify deep and active partnering tasks such that the public role does not replace private R&D opportunities. This includes allocating review and dissemination roles for both public and private partners if a third party (like a university or laboratory) is contracted to conduct work.
- Appropriate ***cost-sharing*** for either general funding or specific projects, and in cash or in-kind services, must be articulated with specific estimates of the industry sector's likely returns in mind. Several scholars argue for the control of funds, subject-matter approvals, and the review of project activities be conducted by an advisory group including stakeholders and neutral parties to ensure a balance between the partners, and between advocates and unbiased experts (Ahearne 1986).
- Finally, regarding ***representativeness***, the literature suggests careful attention be paid to the direct recipients of public R&D funding within an industry to assess whether 1) the industry is actually sharing the costs of applied R&D that will benefit them; and 2) the benefits that those recipients reap are or will be shared with the broader industry such that the program's original societal goals are met. In many cases, an industry group or trade association can be a helpful intermediary if industry innovators are represented, the organization's staff are technically proficient, and the organization has the fiduciary capacity to coordinate cost-sharing.

In some cases, partnerships across government agencies are also critical, but never for management of the program. Most respondents suggest that different governmental entities should not be charged with managing each other's programs or activities. These partnerships should be structured only for coordinating activities across agencies to reduce redundancies and technical conflicts.

Funding

Assuming programs are authorized within their policy and industrial contexts, public-sector funding to the program vision is another core operational decision. In many of the previous cases, appropriated funds had little to do with budget projections based on financial estimates or activities' scope; in several cases, housing R&D programs have been simply carved out of agencies' larger budget appropriations. This reality undermines four core principles noted in the literature:

- ***Appropriateness to the task***. Budgeting accurately is a challenge given the need to both "right-size" for a program or individual project's goals while ensuring that the public-sector investment provides sufficient incentive to hold researchers' and innovators' attention. In the review of past and current programs, budgets were typically ill-suited for both purposes with only a few exceptions (such as ENERGY STAR). Barring clear signals from the industry about the financial gaps in an R&D agenda or estimates of returns from other recent and similar investments, experimentation with project budgets at early stages could lead to identifying the appropriate funding value for specific tasks.
- ***Accurate cost-sharing with industry***. Cost-sharing is a stated requirement in all the literature regarding applied research investments in the public sector, yet the literature rarely assesses how much a cost-share should be for any given activity. Arguably, industries with less of an R&D history and more noted barriers to conducting R&D like housing are less likely to be willing and able to procure a larger proportion of the costs of in a public-private R&D partnership. As noted above, however, public-sector agents must gather as much information as possible when forming partnerships with industry at the onset to be able to specify and negotiate cost-sharing on individual projects and determine the government's share.
- ***Scaling of program to agency's mission***. The size of a housing R&D program's budget can overwhelm the government entity in which it is housed, leading to questions regarding the displacement of entity budgets as well as overall public-sector allocations. As NRC (1986) notes, large R&D programs are easily suspect and can become both political footballs among elected officials and operational targets within government offices. In many cases, moderately-sized programs with modest budgets appear to have the greatest longevity because they are viewed as proportionate to other agency or department decisions.
- ***Stability and continuity***. Numerous scholars of R&D policy and governmental officials that administer housing R&D programs noted that a major aspect of budgeting is that budgets remain as stable and continuous as possible. This aspect affects all other operational conditions, from the confidence of partners, to the identification of R&D activities (which, by definition, requires long-term planning), and to the capacity of managers and staff. One scholar even speculates that unstable and discontinuous funding of public R&D programs is as detrimental as low funding (Ahearne 1986). To this point, a review of the program budgets of the 1990s housing R&D programs since the RAND report demonstrate how stable funding (such as that of ENERGY STAR) may contribute to their success (Figure 4-1). An important corollary to this principle is that it applies to the private-sector cost share as well, and

mechanisms for ensuring commitments for both funding partners must be established early on.

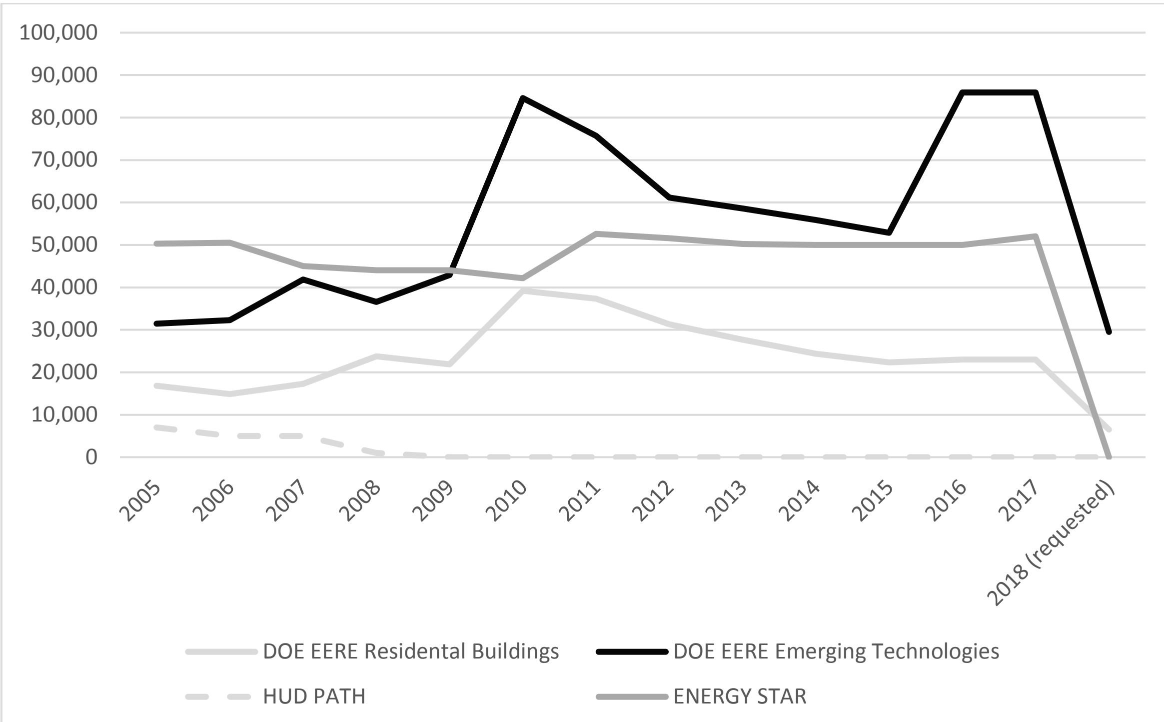

Figure 1. U.S. Budgets for Select Housing-Related R&D Programs, 2005-2018 ($1000s)

Mission

As noted in the discussion of policy context, a clear and articulated societal problem and consequent vision are essential external factors in a housing R&D program's duration and success. How that vision gets operationalized into a programmatic mission that is feasible while still true to the vision, however, is often a stumbling block. As a bridge between the context and operations, a programmatic mission must be articulated well and adhered to. In PATH's case, for example, the original vision came with a mission statement that involved targets that were untenable, and disproportionate to the inputs allotted. Teich (1986) recommends "modesty" in defining and promoting the program so that the program is compelling to external stakeholders like appropriators or the general public and to internal partners. A general mission is also suggested so that a program has room to pivot and revise as industry or policy contexts change (for example, the DOE's turn to retrofitting existing homes in addition to its previous programming around new single-family construction after the 2008 housing crash). Specific targets are better left for more operational goal statements and individual projects.

Goals

A clear theory of change that maps mission-driven goals back to actual resources through reasonable and appropriate activities is a critical, but historically overlooked component of

R&D operations. In the case of housing, innovation is not linear and a causal sequence leading to a goal is not straightforward. However, specific activities can be placed in a generalized sequence such that outputs are predictable and their link to outcomes are supported by evidence.

Two critical flaw in goal-setting for R&D programs are often the assumptions about 1) timeframes, and 2) the direct causal links between a program's activities and economic or societal outcomes. Due to political pressures or exuberant optimism, results and dissemination of innovations are estimated to occur much more quickly than is realistic based on the pace of the housing innovation pipeline. The danger of setting completely unrealistic goals is not just operational, as program's will be perceived publicly and by governmental and industrial leaders as not having met promises.

When they have been employed, goal-setting and logical models for housing R&D programs often have overlooked or purposely avoided placing a program within the world of other R&D activities and incentives that exist in other parts of government or in the reality of the private sector. In too many cases, goals and their targets or other criteria for success will likely be shaped by many other factors (such as the housing market cycles) and not on the technological requirements or feasibility of the activities in question (Ahearne 1986).

Goals, then, must always be contextualized. The use of an advisory board or unconflicted peer review (such as the repeated use of National Academy committees by R&D programs in the past two decades) may be helpful at an early stage.

Activities

Identifying the correct mix of activities to meet the goals requires careful planning not just because each activity may involve different stakeholders (and, hence, different partnerships) but also because there are a variety of possible activities or paths of activities that could, in theory, produce the desired outcomes. The danger of overextending a program based on the number, breadth, and depth of activities is as real as having too fantastic a mission or too many goals. For a housing R&D program, the focus on either 1) a specific stage of the innovation pipeline in depth or 2) providing a clear path for innovations along a more robust spectrum of R&D activities are justifiable options, assuming adequate resources are provided for either. Some scholars argue for the latter, suggesting that a diversification of investments will help weather future changes in the marketplace or political conditions. Programs like DOE's Building Integration efforts support that model, and have been sufficiently resourced to do so.

However, most programs have not had that kind of support. Fortunately, the literature and current program practices provide additional insight into the specific stages that are appropriate for housing R&D interventions, particularly since innovations in this applied research area can easily venture into proprietary territory that unfairly advantages certain parties over others (NRC 1986). Concentrating on the valley between basic research and development (for example through open research calls and transparent joint research findings), and then on the specific barriers to housing R&D (such as information gaps). In many cases, the selection the appropriate activities for a specific stage in the innovation pipeline rests largely on whether there are other programs or public interventions already in place beyond the designated program. In these cases, coordination is essential.

Coordination

As noted in the partnerships discussion early, the success of programs is partially dependent on the range of governmental activities that affect the industry in question. This includes efforts and actions, then, extending beyond partnerships with other governmental entities that are conducting similar or complementary housing research. For housing R&D, this also means monitoring and revising a program's activities within the broader industrial and policy context where building regulations, R&D tax credits, other R&D programs not explicitly tied to housing innovations, and overall housing market shifts also play a role in justifying governmental involvement, and the involvement at a specific stage. These external factors change frequently, and a program must take their presence and likely duration into account at the start to determine whether a long-term investment is possible, and monitor them to ensure that investment is still needed. This lack of regular industry and policy tracking—and willingness to revise or even terminate an activity—was noted as a key factor in an overall program's demise.

Agency

In addition to the above substantive operational factors, there were five areas of logistical operations that were noted as playing substantial roles in a housing R&D program's success. The first of these has to do with the placement and support of the implementing agency or department, particularly when that entity is not an R&D-focused one such as NSF. Mission-driven agencies like HUD, DOE, or EPA are "promulgators of polices" that affect the very industries whose innovative capacities their R&D programs are meant to improves (NRC 1992a). In some cases, those objectives may be in conflict and could pose a problem in partnering.

Program

Even more deeply, the placement and support for an R&D effort within a specific office of that department or agency can be even more material. Office-level budgets and staff resources are smaller than those of the entire agency or department in which they exist. A housing R&D program could then be perceived as taking away from other missions. In a few cases, interview respondents noted that this tension eventually led to competition for resources, active dissent against the R&D program, and reduced overall support from the larger agency or department itself over the long term.

Management

The instability of research direction especially because of changing policymakers was noted cause of failure from a policy perspective (Ahearne 1986). However, capacity throughout an organization's hierarchy can be just as critical for a program's success—and failure. Operational managers who can inform senior leaders and policy makers while maintaining the day-to-day communications with industry and other governmental partners are critical to ensuring that any one R&D activity produces its expected outputs. Given current perceptions of governmental efficiency, the potential for any program to be denounced as a failure due to the discrepancy of one activity is particularly challenging. Along with well-versed managers, the inclusion of frequent and well-organized reviews that provide management guidance along with subject-matter expertise can help mitigate this factor.

Staff

The quantity and skills of housing R&D program staff were described as another key logistical impediment. R&D program staff with a poor understanding of the current state of technology were identified in past efforts as ingredients for failure (Ahearne 1986). However, other scholars and officials pointed to the need for technical staff capable of analyzing the marketplace and industry as much as the physical design, engineering, and construction areas in question. Both skill sets were described as necessary to being able to design and monitor appropriate programs and activity interventions, and to flesh out balanced research work scopes and products, and to procure fair industrial partnerships.

As a complement to the governmental staffing capacity, respondents also noted the skills of industry staff, researchers, and third-party investigators in being able to deliver quality research or research guidance. Where the eventual research quality was compromised, it was difficult to maintain robust industry partnerships except for the immediate beneficiaries of research funds. Design programs and activities to permit the participation of the maximum number of industry staff and scholarly researchers, and promoting peer review at all stages, was noted as mitigating strategy for this.

Monitoring and Evaluation

Finally, the proof of research results and contributions to mission outcomes—and, more importantly, positive and significant impacts to a program's broader societal goals were noted as another key logistical component of program operations. In many of the early program cases, formal monitoring and evaluation has been conducted only after a program's demise. More recent programs have established both internal and external reviews more systematically, due largely to government-wide requirements such as the Government Performance and Results Act (NREL 2009; NRC 2001, 2006). Regardless, the creation of a monitoring and evaluation plan at a program's launch, however, was consistently described as helpful for goal-setting as well as documenting changes in the industrial and policy landscape.

Putting the Innovation Model into Context

Previous work explores how technological and industrial subject areas even within the already circumscribed world of the housing industry have unique innovation pipelines. As this paper suggests, however, interventions into that pipeline are also idiosyncratic. Policy and market contexts play a critical role in determining whether any innovation intervention is conceptually feasible, underlined by political philosophies regarding the roles of government and industry in promoting innovation in an applied area like housing. Specific policy ingredients are as significant contributing factors to a program's success after launch—from the conceptual strategies and selected activities that a housing R&D program employs to the operational inputs that define the day-to-day progress towards improving the innovation pipeline and meeting societal needs in any way.This review of past and current housing R&D programs provides historical insight into each of these factors and their contribution to program success.

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SOCIAL HOUSING ARCHITECTURE AS A GENERATOR OF SOCIAL PRACTICES

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ABSTRACT

Social housing and mass housing systems are applied as a solution to the problem of housing shortage that ensue from urbanization process. The housing problem that emerged with urbanization has been tried to be solved by different solutions within the scope of the social housing policies that states have produced. While some developed social housing projects for the topic succeeded, wrong policies accelerated the formation of informal settlements. In this paper, the effect of the level of user participation and the process in the social housing for low-income people was investigated through the samples and the positive and negative effects were tried to be visualized. In accordance with this purpose, some architectural examples from Turkey and the world were selected and the study being conducted on these examples such as SAAL (Serviço de Apoio Ambulatório Local) Bouça Porto(Portugal), TOKİ (Turkey), Viranşehir Su ve Toprak (Viranşehir Aqua and Earth) (Turkey), Düzce Umut Evleri (Düzce Hope Homes) (Turkey), Quinta Monroy (Chile). The examples were selected considering varied roles of actors (low-income people, the government and designers) which are included the process of social housing production.

Keywords: social housing, low-income groups, participation

1.INTRODUCTION

Urbanization is one of the most important process that makes visible the change of community life. The environmental and physical changes cause human relationships to alter and human behavior to adapt to the new environment. Until the 1980s, especially in the developed countries, governments played an important role in social housing policies and housing production. In the developing countries, slums and illegal buildings have emerged because housing problems have been ignored without being solved (Kara, 2012). All over the world, approximately one billion people live in informal settlements and are expected to double this number in the next 20 years (Beardsley, 2007). Informal settlements, especially in developing countries, such as 'slums' in Turkey or 'favelas' in Brazil, create urban areas as dominant forms.

There are new methods and studies developed to enable the unplanned construction to be controlled and to facilitate the adaptation to urban life. The underlying cause of the problem is that low-income users do not have enough budget to be a resident, and they try to meet their needs with informal means and their own unique solutions. It is possible to talk about various groups of actors depending on the political and socio-economic situation of different countries in the formation of low cost and affordable housing solutions. Social housing for low-income families contains different actors which have an active role in the design and construction phase. These actors involve; low-income users, the government, investors, non-governmental organizations and rarely designers. This paper will focus on the contributions and activities of actors, low-income users, government and designers.

Social housing designs have begun to standardize with modernism in order to accommodate more populations in the minimum space and enable rapid production. After the drawings of Ville Contemporaine designed by Le Corbusier in 1922, it started to build up in density with the vertically rising buildings. The rapid and mass production of the building blocks started to grow in the same solid forms in different geographies without considering the environmental factors, and the relationship between the living spaces that they formed and the environment created by the users and the environment started to be questioned. One of these mass housing production models is the Pruitt-Igoe mass housing which is designed by Architect Minoru Yamasaki in Saint Louis, United States. The Pruitt-Igoe housing complex, consisting of 11 floors, 33 blocks and 2,740 residential units, was demolished in 1972 from security problems. Newman (1966) notes that although the ground and first floor are left empty for public use, the occupancy rate of the blocks never exceeds 60%.

The human-centered thought movement that started to be active in the arts and social fields in the 1960s contributed to the idea of user participation in the space design and decision processes by influencing the architecture. Jones (2005) defines the mood of the 1960s as 'optimistic, utopian, equalitarian and extraordinarily open'. In addition, with this period, ‘the user’ in architecture with criticism of modernism; at CIAM (Congres Internationaux d'Architecture Moderne) congress the borders have been transformed from ‘the passive user’ who has been passivated by the defined spaces defined by the designers to ‘the active user’ who is considered by the variable and transformable forms like Archigram.

In the 1970s, the first examples of user participation have begun to be practiced in residential projects. Walter Segal's ‘Borough of Lewisham’ social housing project, where the user is involved in the construction process, is one of the first examples in this practice. This experience is an important project for the period as well as being a small and limited experience in order to construct its own environment and living space (Jones, 2005). After the 1970s, changing government policies, changed the understanding of the social state, and people with economic inefficiency began to live in social housing located outside the city. The ‘site and service’ system, initiated by The World bank and John Turner, the ‘support and infill’ system developed by John Habraken and SAR(Stiching Architecten Research) group, the ‘incremental housing system’ experimented by Hasan Fathy, Lucian Kroll, and Alejandro Aravena are some of the residential systems built with the aim of involving the user in the process.User participation patterns in social housing continue to evolve today with different system and form suggestions of designers and planners.

In this research, the effect of the level of user participation and the process in the social housing for low-income people was investigated through the samples and the positive and negative effects were tried to be visualized. This paper, treats the social housing as an architectural system. With this point of view, the aim of thesis is to analyze architectural characteristics of the selected building groups, to investigate interactions and relationships between physical spaces and corresponding social practices in these systems; which physical features of architecture support or non-support community's social life, social interactions and its potentials.

2. THE SOCIAL HOUSING PROCESS AND ACTORS

The aim of the study is to examine the contribution of the low-income user participation, which is one of the actors active in the social housing productions for the low-income group. The study is proposed to reinvestigate through social housing that the architecture creates life beyond produces a physical entity. In accordance with this purpose, some architectural examples from Turkey and the world were selected and the study being conducted on these examples such as SAAL (*Serviço de Apoio Ambulatório Local*) Bouça Porto (Portugal), TOKİ (*Housing Development Administration of Turkey*) (Turkey), Viranşehir Su ve Toprak (*Viranşehir Aqua and Earth*) (Turkey), Düzce Umut Evleri (*Düzce Hope Homes*) (Turkey), Quinta Monroy (Chile) (Figure 1). The examples were selected considering varied roles of actors (people with low-income, the government and designers) which are included the process of social housing production. Thus, in the design and construction process chosen examples were categorized under 3 sections by the roles of these actors.

- Examples which the user (low-income people), designer and government have equal roles in design and construction phase. The examples are SAAL Bouça Porto, Portugal and Viranşehir Su ve Toprak (*Viranşehir Aqua and Earth*), Turkey.
- Examples which the government has a dominant role in the design and the construction phase. The example is TOKİ Emlak Konut Tuzla 1. Etap Konutları (*Emlak Konut Tuzla First Stage Housing*), Turkey.
- Examples which the user (low-income people) and designer has a dominant role in the design and the construction phase. The examples are Quinta Monroy, Chile and Düzce Umut Evleri (*Düzce Hope Homes*), Turkey.

For tracing the effects of architecture on the social practices, selected social housing projects will be analysed according to predetermined criteria based on relationships such as; roles of actors, user participation and relation between actors in process of social housing. In addition, site plan of the settlement and settlement's relation (physically) with environment, public/private space, user/environment relationships in these settlements will be analysed for each project.

Figure 1. Location projects analyzed from Chile, Portugal and Turkey

2.1 Examples which the user, designer and government have equal roles at the design process of social housing

In this section, SAAL Bouca Porto and Düzce Hope Homes will be examined in the case of low-income users, designers and government actors have equal roles in design and construction process of social housing.

SAAL (Serviço de Apoio Ambulatório Local)- Bouça Porto, Porto, Portugal

In 1974 SAAL was established in cooperation with the designers and the government to meet the housing need for low-income people living in bad conditions in Portugal after the Portuguese Revolution. This foundation aims to realize the social housing production that the user can include in the process. Afterwards, with the involvement of architects such as Alexandre Alves Costa, Álvaro Siza Vieira and Gonçalo Byrne, and with the local people running the design process, SAAL began to produce houses in many parts of Portugal, receiving much attention. Many different architectural groups, architects, and students have created different methods and forms to generate designs that incorporate traditional elements. SAAL Bouca Porto, designed by Alvaro Siza, is one of the 33 project sites that were built in Porto in 1975 (Figure 2). One of the most important difference between SAAL projects and user participatory social housing is that the operation had to be requested by the residents. Another one is that group of residents who required a SAAL operation , had to organize themselves and certify the agreement between each other with a notary (Bandeirinha, 2014).

SAAL has made it possible for local people to be involved in the housing production process and to improve their physical conditions without losing neighborhood relations. Instead of taking a dominant position, the architect has a more equal attitude, allowing the user to integrate with the project and take responsibility. The project, which can be called as mutual learning and experience, minimizes the conflict between the local and the later articulation as well as the interdisciplinary communication network (Baia, 2014).

Figure 2. SAAL Bouca Porto settlement (on the left) and the atrium viewpoint (on the right) (Url-1)

The location and relationship of housing, public spaces and official building provided private backyard, although they are not surrounded by any external walls. The related/unrelated situation with the railway station is shows that the potentials of the area and environmental factors could be transformed into positivity by design decisions (Figure 3).

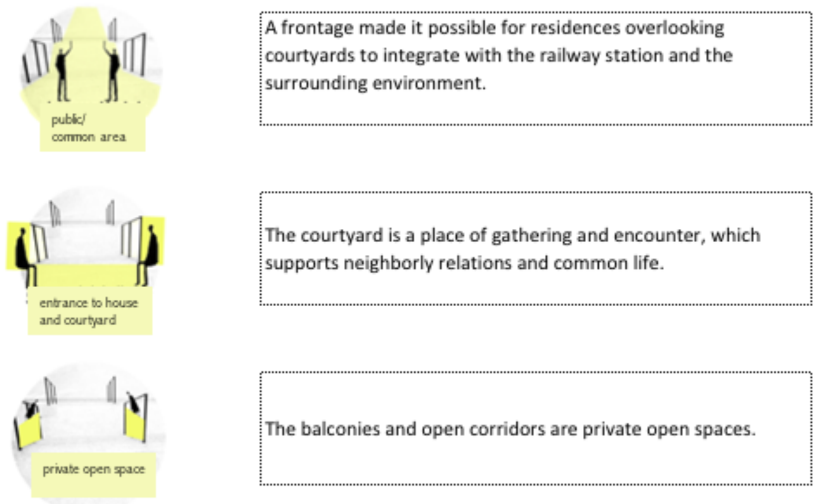

Figure 3. Public/private space, user/environment relationships in SAAL Bouça Porto

In the SAAL Bouca Porto project, the user has organized itself and requested housing from the government. Although the user does not actually contribute to the design process, the user has been actively involved in the transmission of lifestyles and requests. As well as in many projects under the scope of SAAL, in this project low-income users have also worked in the construction phase.

Viranşehir Su ve Toprak (Aqua and Earth), Şanlıurfa, Turkey

The project aims the housing of low-income families in Şanlıurfa's Viranşehir province started in 2009 (Figure 4). The main theme of the project, which is called an ecological and communal village experiment, is to produce affordable housing with local materials. Initially, meetings were held in which women and children also participated. The common living and working conditions for a new life model have been determined in the community formed by the arrival of families from different origins for the first time.

Figure 4. A family with four children living in Viransehir dwellings (Url-2)

Users who started to build their own homes on the land allocated by the government received help from the designers throughout the process. Interest in the project has increased with workshops and meetings organized by different groups both at home and abroad (Figure 5). Alker (building material consisting of gypsum and mud brick), which was developed from the idea of mud brick which is ecologically and inexpensive building material, was determined as the main building material and it was decided to be used for the construction of the houses of its own.

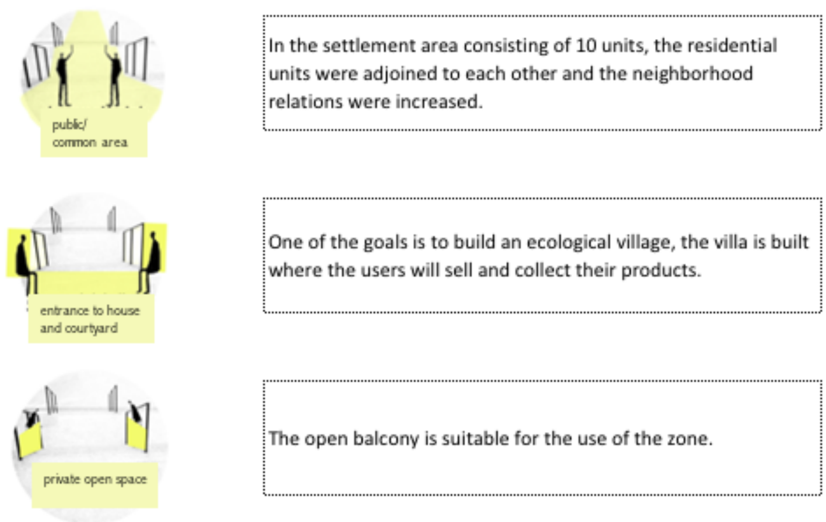

Figure 5. Public/private space, user/environment relationships in Viransehir

At the end of the project, 10 houses have been completed, the budget has been exceeded due to the fact that the individuals working in the house construction can not do any other work, continue to pay rent, and the area of the houses are too big. The users who settled in their houses after the completion of the project made unique changes in their houses. With these changes, differences are observed especially in the interior and exterior finishing elements of the houses which were initially constructed as the same type (Figure 6).

Figure 6. Before (on the left) and after (on the right) outside of houses in Viranşehir

Despite the design of self-sufficient residences using ecological and natural materials, the users continued to make changes and adjustments with aesthetic concerns after they started to live. To make it look more modern, the ceilings and walls were covered by the users and the facade was modified (Figure 7).

Figure 7. Before (on the left) and after (on the right) inside of houses in Viranşehir

At the beginning of the process, everyone was expected to collaborate without determining which house belonged, but in progress of construction, each family was directed only to build their own house.

2.2 Examples which the government has dominant role at the design process of social housing

In this section, TOKİ Emlak Konut Tuzla 1. Etap Konutları (*Emlak Konut Tuzla First Stage Housing*) will be examined in the case of the government has dominant role in design and construction process of social housing.

TOKİ Emlak Konut Tuzla 1. Etap Konutları (*Emlak Konut Tuzla First Stage Housing*), İstanbul, Turkey

A state-run social housing provider TOKİ (Housing Development Administration of Turkey) was established with the Law on Mass Housing which was issued in 1984 in order to solve the housing problem. In 1990, it was organized as two separate administrations in according to Laws Numbers 412-414 and the Presidency of the Housing Development Administration and the Public Sector Administration. In 1993, due to the mass housing fund being taken to the General Budget, the housing production was interrupted for a while. Between 1984-1988, the institution has provided extensive credit support to cooperatives, and until 2002, 43,000 houses were completed in 19 years, and approximately 950,000 houses were financed (Url-3). Between 2003 and 2009, the institution became active in 81 cities and 800 towns and produced 420,000 housing units in 1622 construction sites. TOKİ completed 623,000 social housing units by November 2016.

The low-income user has been the subject of many researches in terms of the relationship between the user and the living space that the government produced by ignoring the environmental data with the motivation of the owner. The government produces new living space by ignoring regional and environmental data for the purpose of making low-income users residential. The effects on the user's spatial relationship have been the subject of many researches. In different countries, studies have been carried out on the relationship established by the dwellings, the satisfaction of the users and the sustainability. In some of these studies, the user is spatially pleased, while others complain about the lack of public space (Es, 2014, Turan, 2010, Freitas et al., 2015). It is not very realistic to make a generalization of the results, but the common dissatisfaction of the users is very far from the workplaces and city centers and the lack of common areas can be stated.

In this study, rather than the spatial characteristics of the social housing that are produced as mass housing, the production processes are considered. The actors who are active in the social housing production process mentioned above will focus on what stage they are active and passive in the case of TOKİ Emlak Konut Tuzla First Stage Housing completed in 2016 (Figure 8).

Figure 8. TOKİ Emlak Konut Tuzla First Stage Housing (Url-10)

Tuzla First stage Housing, which consists of 18 Blocks 666 residences and 8 commercial units built on a total area of 48.764 m2 in Tuzla district of Istanbul by Emlak Konut which is an participation of TOKI, was completed in 2016. Before the decision of the project, the market analysis studies were made on the field and the data such as expectation from target group, preferred type of residence and living area were obtained.

For the social housing built by the project designing group, floor plans and block layouts are determined according to the district density by using the previously determined standard plans. In the system where the problems experienced in applying the application projects to the field are solved by the field architects, the designer architect is only involved in the drawing phase (Figure 9).

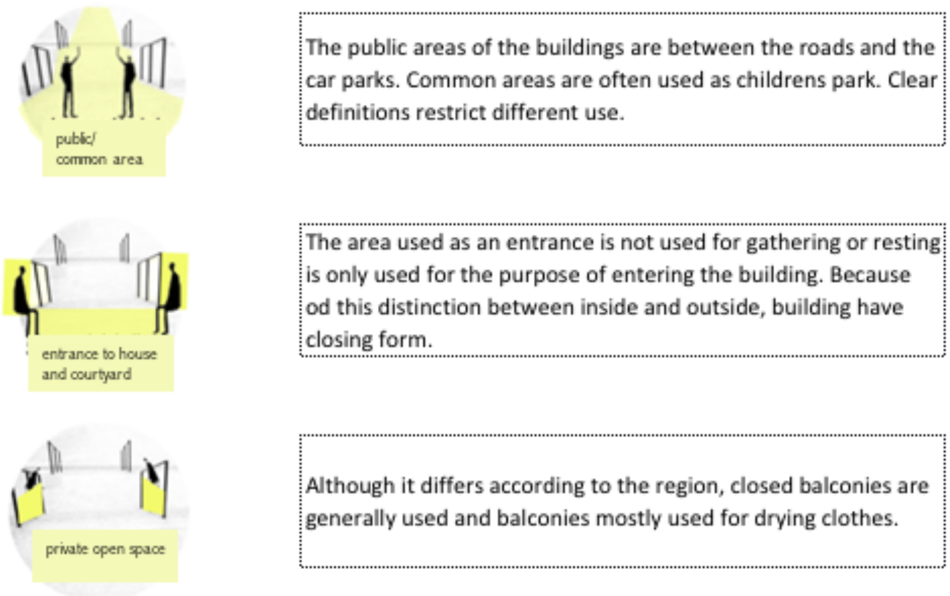

Figure 9. Public/private space, user/environment relationships in TOKİ Emlak Konut 1. Etap

In the TOKI project system, the designer takes part as an actor in charge of producing projects that allow rapid and serial production in accordance with predetermined standards in the production process which is under government control. The user is active through the questionnaires in the beginning process, but it is acting as an ineffective actor until the housing delivery date.

2.3 Examples which the user and designer have dominant role at the design process of social housing

In this section, Quinta Monroy and Düzce Hope Homes will be examined in the case of the user and designer have dominant role in design and construction process of social housing.

Quinta Monroy, Iquique, Chile

The Chilean government has decided to launch a program called Chile-Barrio in order to be a solution to the increasing housing problem in the slum areas. The aim of this program, launched in 2002, regionally, to ensure that people living in slum areas are homeowners with a $10,000 budget to be paid by the government. Quinta Monroy, chosen as the pilot district, is a region where the slum areas of the city of Iquique near the Chilean desert weigh heavily (Figure 10).

Figure 10. Quinta Monroy, after the users started to use houses

For the planned project in the Quinta Monroy region, government officials started the project process with a group of designers and entrepreneurs from the architectural office ELEMENTAL, Chile Oil Company and Pontifica Universidad Católica de Chile. User participation is provided in the entire design and implementation process of the houses to be built on the land allocated by the government with low loans. The designer and the user interacted with each other in order to make a co-decision, and a new housing model was created by the designers evaluating and interpreting the users' requests. Since the budget provided by the government does not allow for the production of the targeted 80 m2, it has been approved to design a 40 m2 section, which is a house half.

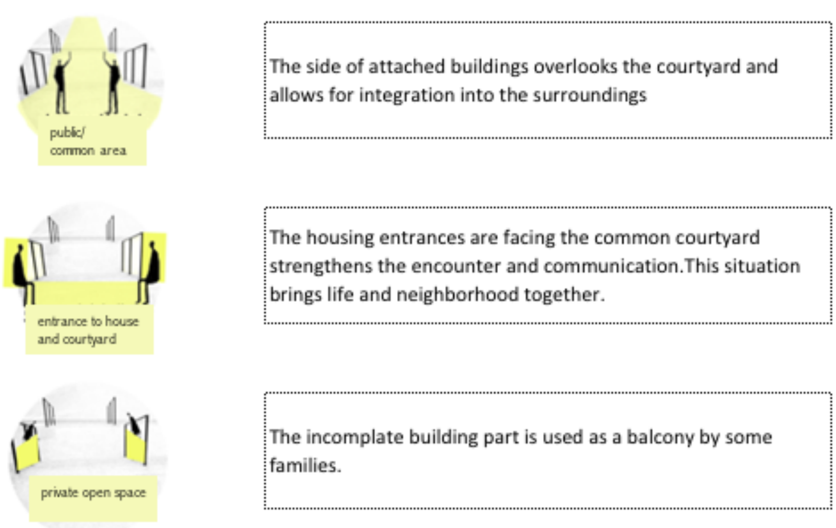

Figure 11. Public/private space, user/environment relationships in Quinta Monroy

The remaining 40 m2 of residences continued to change after they were delivered to their families. While some 40 m2 of space left to the family were taken home by some users, some users preferred to use it as an outdoor balcony (Figure 11). The government actor played an active role in determining where social housing is to be built and in the execution of the financing process. The designers involved in the process with the proposal of the government undertook the intermediary role between the government and the user and produced new solutions in order to meet user demands as much as possible. The user has been involved in the construction process during the application phase while actually working with the design phase demands. The users made changes in the facade and interior (Figure 12). One of the distinctive and unique features of the project is that the user continues to build and change after the construction process is completed and the houses are delivered to their owners.

Figure 12. Before (on the left) and after (on the right) outside and inside of houses in Quinta Monroy (Url-5)

Düzce Hope Homes, Düzce, Turkey

After the August 17, 1999 earthquake, the equally treated earthquake victims were separated as property owners and tenants in the case of permanent housing. In 2002, when it came to the removal of provisional housing places, the tenants made attempts to resolve housing questions. In 2004, the Ministry of Public Works and Settlement announced that low-income citizens, according to Law No. 775, would allocate 6 shares for residential needs. After years of searching for legal process and rights, TOKİ has approved the transfer of Düzce's land in the Beyköy district of Düzceli Tenants' Earthquake Rescue Cooperative (Url-6).

Design decisions were taken in the direction of 'workshops' made with the users in the project that the participation of the users was decided in the design and implementation process. Düzce Umut Atelier, which consists of designers and planners, organized workshops for different age groups from different age groups at different times in order to be able to create designs in the direction of user requests (Figure 13).

Figure 13. Workshops with families and children in Düzce Hope Homes

In the first workshop dated February 8, 2015, Düzce Umut Atelier played a residential, social and green space placement game with 189 rights holders and families on 3 parcels of land models in Düzce. Later, women, children, young, old and male focus group work was done. The resulting data were analyzed at meetings, and settlement plans began to form. The general orientation of the members was that they wanted places where they could be together again in the residential areas. It was decided to create a courtyard system in the design of the site plan.

Düzce Umut Atelier performed the 2nd Düzce visit to play the design game which focuses on the residence. In the scope of the game, the units prepared in different square meters were placed together with the members, and the requests for square meters and number of rooms were analyzed.

The third meeting was held in Düzce, and the results were analyzed and the alternatives of the floor plan and apartment types were shared. The questions and opinions of the cooperative members were taken. Alternatives were revised according to the proposals.

In the 4th meeting, an exhibition was organized in order to contribute to the construction process. Düzce Umut Atelier and its co-operative members took the decision on the principle of not carrying out revisions which would ignore the participatory process taking cost concerns into account. A campaign was designed to facilitate the construction process, inspired by the "Struggle Together" and "Together Design" processes (Figure 14).

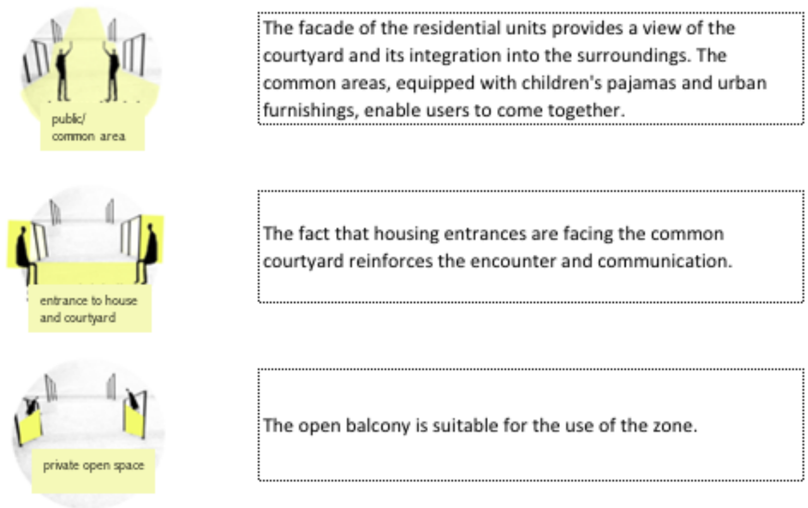

Figure 14. Public/private space, user/environment relationships in Düzce Hope Homes

The construction process started in October of 2016 and the construction of the building site was carried out together with the partners and volunteers. The construction process cooperative, which is open to voluntary participation, and Düzce Umut Atelier continue in cooperation (Figure 15). Focusing on the fact that the participation is process-oriented rather than outcome-oriented, the participants live the excitement and motivation of the project which will be realized for the first time in Turkey.

Figure 15. Düzce Hope Homes construction site (Url-6).

3.CONCLUSION

In this study, the level of user involvement and impact on the process in social housing for the low-income group were examined through examples. The actors who are active in the production of social housing, the low income group, the user, the government and the designer are examined and the actors involved in the design, implementation and management processes are examined. In this context, while selecting sample projects, attention has been paid to different geographies and applied projects. Projects according to actors' active and passive status; the designer, the user and the government are active, only the government is active and the user and the designer are active examples are collected under three headings (Figure 16).

SAAL Bouca Porto and Viransehir Su ve Toprak projects have been selected as examples of low-income users, designers and the government actively involved. For both projects, the user requested land demand from the government. The SAAL was an user participation project, but the user was not actively involved in the design phase and the life traces observed by the designer were transferred to the project. The situation in Viranşehir was similar and the user intervened and insisted on the housing accounts of the houses. Land cost, low state loans have been paid by the user. During the designer implementation period which was active until the end of the SAAL Bouca Porto project, the Viranşehir project was taken after a while and the user completed his own house. In both projects, the user actually worked in the construction phase and used the work force. Users who make changes in the Viransehir project, especially in the interior of the house, with a modern look and the use of interior finishes negatively affect the natural balance of Alker (building material consisting of gypsum and mud brick) natural building material. Breathing and unhealthy materials begin to deform over time.

The example of TOKİ Emlak Konut Tuzla First Stage Housing project in Turkey is examined in the case of the government being active in social housing production. In the housing models produced by TOKI according to the general standards, the user is only involved in some questionnaires made at the preliminary stage of the project. The construction process was carried out by a different architectural team and the user was not involved in the area until the finished product. Houses are designed by the designers of TOKI in accordance with the determined standards, depending on which of the common housing models (2 + 1, 3 + 1, 1 + 1 plan types) the user prefers in the direction of the surveys before the project . The application of the same type of housing in areas with different physical and climatic characteristics is a general criticism of this housing production system and is one of the negative effects of being located in remote areas of city centers.

Quinta Monroy and the ongoing construction of Düzce Umut Evleri, which are examples of low-income users and designers actively involved, have been examined. The project process has been started on the basis of the user participation on the land allocated by the government with low payment plans in line with the request for housing acquisition from the user. In both projects, the user is fully involved in the process with a 'workshop' in the design phase. The user, who is active in giving design decisions such as site plan, apartment plans, public / common areas, facade design, has actively worked in the construction phase as well. The architects who created the designs in the direction of the user's demands have undertaken the task of guiding the users with minimum intervention. Considering the cost in the Quinta Monroy project, the main core of the dwelling (structure and wet spaces) was created with the financial assistance provided by the government and the user was scheduled to complete the other half of the dwelling over time. Thus, nowadays we see that the users have completed their dwellings and that every dwelling has an original facade. On the Düzce Umut Evleri project, the result shows that the participant process is a 'placatory participation process' because the outcome is a housing model with a commonly used plan type (3 + 1, 2 + 1 plan types). It can be seen that the requests from the user can not be stretched.

Viranşehir Su ve Toprak and Düzce Hope Homes projects are the housing projects in Turkey where the user is actively involved in the process. These are examples of housing projects designed specifically for low-income households and partially successful. The fact that the construction process of the Düzce Hope Homes project is ongoing is premature to produce discourses about the outcome, especially those experienced in the design phase, reinforcing the relationship between the architect and the user. It has been observed that the user has adopted the project and tried to contribute to it. It is important to note that these examples show that participation is a multi-faceted and challenging process for us.

The aim of the low-income user to be included in the design and construction of the housing process is to adopt the user's habitat and gain a sense of belonging to the urban life. The user who tends to change or abandon a place that he or she can not identify with herself, is adapting more quickly to the areas it can change and transform. It has been observed that social housing projects in which the user is active in the application and design stage in the direction of the readings and studies have different levels of participation and design approaches within themselves. In social housing designed and implemented without consideration of the user, it is considered that the problem of adaptation experienced by the user will be intensified with participation and increase the continuity in the living spaces. In particular, 'user participation' will play an important role in creating systems that can provide solutions to illegal housing acquisition.

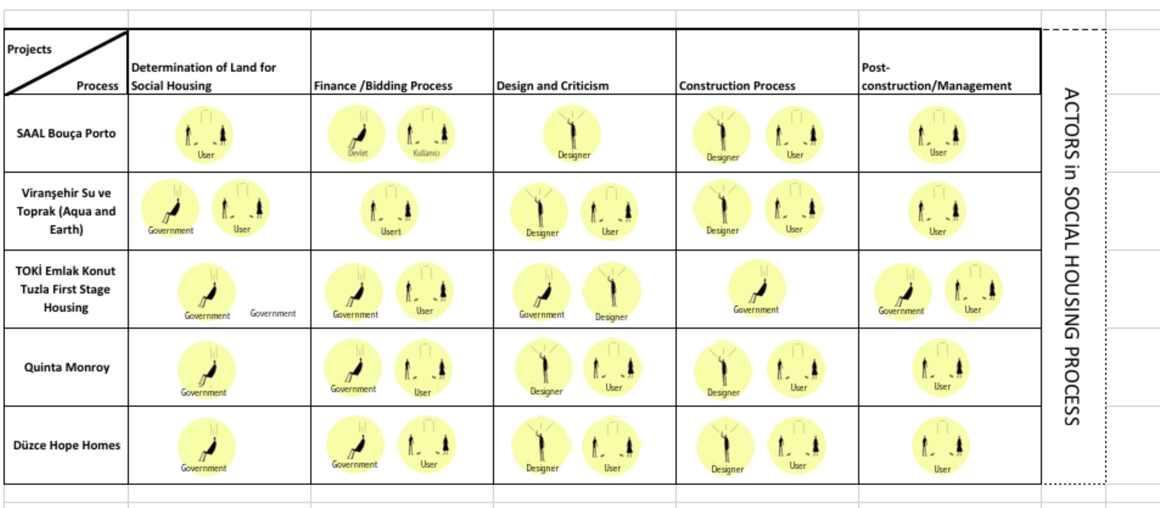

Figure 16. Actors in project process.

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Three Courses/Four Typologies: Experiences with the 2017 Race to Zero Competition

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ABSTRACT

The Race to Zero student design competition is sponsored by the US Department of Energy. Competing teams are challenged to develop and present proposals for small residential projects that embody low energy consumption achieved through the wise design of enclosure elements and systems components. Four building typologies (competition categories) were available to the 2017 student teams: suburban single family, urban single family, attached housing, and small multifamily. Mandatory competition deliverables included a draft status report, a final report, a one-page summary sheet, and a face-to-face presentation to jurors. Optional deliverables included a poster and a physical model. Teams work on the competition for either one or two semesters/terms. The competition culminates at the National Renewable Energy Laboratory (NREL) in Golden, Colorado.

This paper presents experiences resulting from the involvement of four student teams from Ball State University in the 2017 Race to Zero. These four teams, involving over a dozen total students from architecture and construction management, each addressed one of the project typologies. Three faculty members were actively involved with the teams, as were several external partners. The teams benefited from a collaboration among three distinct courses—a graduate level comprehensive design studio, and two graduate electives (one focusing upon energy modeling and one upon LEED for Homes). Independent study opportunities in construction management brought a further dimension to the teams' efforts and solutions.

This paper describes the context of the Ball State University participation in the Race to Zero and explores the synergies that developed among the four teams, the three courses, the faculty, and the external partners. The educational benefits of participation are addressed.

THE RACE TO ZERO

The Race to Zero (RTZ) student design competition is sponsored by the US Department of Energy (DOE). The 2017 Race to Zero was the fourth annual student competition. As described by DOE: "The competition challenges collegiate teams to apply sound building science principles to create cost-effective, market-ready designs that meet DOE's Zero Energy Ready Home program requirements ...“ (NREL, 2017) A stated objective of the Race to Zero program is to “advance building science curricula at universities” and to prepare the next generation of architects, engineers, construction managers, and other professionals to solve real-world problems related to net-zero energy residential design. (USDOE, 2017)

Competition rules expand this general expectation for the development of high-performance building solutions by specifying ten specific areas of evaluation to be considered by competition jurors. These areas (each worth 10 points in the overall evaluation process) are:

1. Architectural Design
2. Interior Design, Lighting, and Appliances
3. Energy Analysis
4. Constructability
5. Financial Analysis
6. Mechanical, Electrical, and Plumbing Systems Design
7. Envelope Performance and Durability
8. Indoor Air Quality (IAQ) and Ventilation
9. Innovation, and
10. Presentation and Documentation Quality

It is clear from the information provided to prospective competition entrants that the Race to Zero expects comprehensive design proposals that coordinate and integrate enclosure and mechanical-electrical systems. It is reasonable to state that development of design solutions to this level of refinement—while verifying projected performance against prescribed software and checklists—is not the norm in North American schools of architecture. Thus, the allure of the Race to Zero for several educational institutions—including Ball State University.

The 2017 Race to Zero competition offered four categories of housing typology. These were: suburban single family (SSF); urban single family (USF); attached housing (AH; duplexes or townhouses); and small multifamily (SMF; 3 stories or fewer). Each typology had specific building area (or unit area) and site area requirements. Teams chose their own sites. A collegiate institution could submit one proposal per contest (or four in total). Each building typology constituted a distinct “contest” within the larger competition—with individual category winners. A grand prize was also provided for the best of the four category winners.

Preliminary 2017 Race to Zero competition information was available to teams in early fall 2016. Registration closed on 1 November 2016. The competition presentations took place in late April 2017 at the NREL facilities in Golden, Colorado. Thus, depending upon individual academic circumstances, a team might have at most two semesters (or terms) to develop a solution; at minimum, a team would have one semester (or term). The competition required submission of a preliminary progress report on 28 February 2017; completed submissions were due on 4 April 2017. Teams were strongly encouraged to bring a poster presentation to the NREL event; a project model was also encouraged.

Training was an integral aspect of the Race to Zero competition. Team members were required to complete 12 online building science training modules and were given access to a number of informational webinars and software resources to assist in their project development (an important example was student access to REM/Rate software to generate a HERS rating).

THE RACE TO ZERO AT BALL STATE

The Ball State University Department of Architecture is part of the College of Architecture and Planning (CAP). CAP, at the time of the 2017 Race to Zero, included programs in architecture, landscape architecture, urban planning, and urban design. The construction management program at Ball State was housed in a separate college (CAST)—although this had virtually no impact on cooperation and coordination. Ball State does not have any engineering programs. In 2017, the accredited degree in architecture was a 4+2 Masters of Architecture—the 4 denoting undergraduate years and the 2 representing the length of the master's component. This is a fairly common approach to delivering an accredited degree in architecture.

The National Architectural Accrediting Board (NAAB) requires accredited architecture programs to demonstrate that graduates can "synthesize a wide range of variables into an integrated design solution." (NAAB, 2014) At Ball State University, this requirement is primarily addressed in the graduate level Arch 501 Comprehensive Design Studio. As the course name suggests, this studio challenges students to conceive, develop, and execute projects that address a wide variety of design considerations including, but not limited to: site design and orientation; programming; cost analysis; occupancy and human context; interiors and indoor environmental quality; structure and environmental systems integration; material selection; energy and environmental impact; etc.

A significant challenge of the Arch 501 studio is selecting a project through which students can attain a high level of detail in a short period of time (16 weeks). The Race to Zero student design competition was an ideal solution to such challenges for at least four reasons: (1) the competition focused on housing, which meant that the projects were small scale and manageable for students; (2) the competition focused on team work, which meant that students could share work and expertise as they developed projects in detail; (3) the semester and RTZ competition schedules aligned relatively well; and (4) the competition encouraged involvement of industry professionals to help students with limited skills or knowledge regarding certain technical aspects of building design to better develop their proposals.

Team Structure. The 2017 Ball State University RTZ team structure is illustrated in Figure 1. The core design teams were situated in the Arch 501 design studio, which was led by Assistant Professor Tom Collins. Ball State students entered all four housing typology contests (the only university in the 2017 RTZ to do so). The suburban single-family (SSF) team was not formally enrolled in the studio and operated semi-independently—while using the studio as a home base. All four teams worked with students from two graduate architecture elective courses, which were led by Professor Walter Grondzik. The Arch 632 High-Performance Buildings course focused on energy modeling and the Arch 633 Advanced Technologies for Green Building course focused on LEED for Homes compliance. The architectural design teams also worked with an independent study course on cost estimating, which was led by Associate Professor Tarek Mahfouz in the Department of Construction Management. The core teams also worked with four industry partners outside the university, who provided feedback on housing design strategies, HVAC design, green design strategies, and photovoltaic system design. Altogether, all four teams heard (and ingested) a robust assortment of voices on a wide range of design and technical considerations.

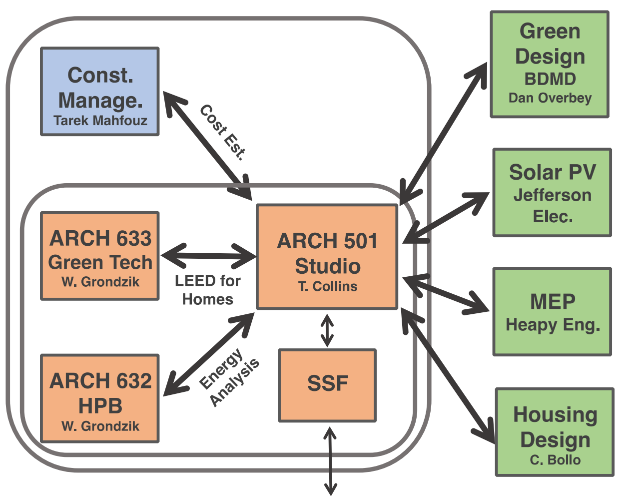

Figure 1: Diagram illustrating the course and industry partner collaborations for the Ball State RTZ teams.

Design studio (Arch 501). The Arch 501 Comprehensive Studio course initially had eight first-year graduate students (five male and three female). The semester was divided into four stages that corresponded with the RTZ schedule. The students self-selected into two teams with three members each and one team of two members.

Stage 0 included the first three weeks of the semester and involved preparatory work such as beginning the required building science training, assembling the architectural design teams, establishing communication channels with the consultant courses and industry partners, and becoming familiar with the competition expectations and previous entries. Students used a speed-dating technique to select team members. Each student interviewed every other student in the section asking about work habits, skills, interests, etc. This avoided friends working with friends and ensured good group dynamics. Stage 0 was intended to tide us over until the final version of the competition guide was available at the end of January. In hindsight, the final guide was not much different than the preliminary guide and the design process could have begun earlier.

Stage 1 roughly corresponded to the month of February—leading up to the submission of the Progress Report. The report was ten pages maximum and asked students to provide some baseline metrics for their scheme, a description of their site, and their initial design goals or intentions. No technical design was required at this stage. Students worried, however, that without a strong scheme, they would not advance to the final round of the competition. Race to Zero materials even suggested that students be further along with their schemes than the report required them to demonstrate. We used this time to focus on finding a site, describe the site context, and create a strong design concept for the project. In hindsight, much of the Progress Report could be easily compiled in the first few weeks of the semester.

We had an internal design review with faculty members after the Progress Report submission where students received constructive criticism on their schemes. One critique was that the floor plans needed to better accommodate housing market trends in terms of spatial arrangements, amenities, room sizes, etc. Following this review, we added an industry partner with expertise in housing design to provide additional feedback. We also received our first round of feedback from the architecture and construction management support courses in addition to the other industry partners. In exchange, we shared up-to-date area takeoffs and other design information with the support courses as they began their cost estimating, energy modeling, and LEED analysis. All four teams advanced to the final round after the NREL review of the Progress Reports. The teams knew beforehand, however, that the studio would continue with the same design development effort regardless of finalist status.

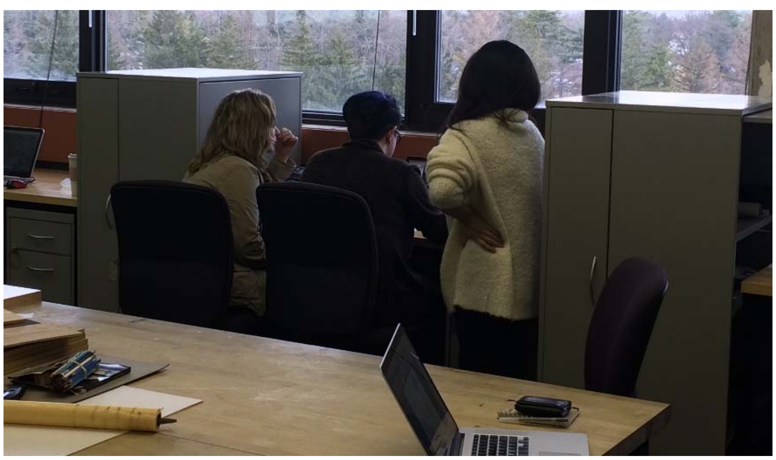

Figure 2: A team working collaboratively during studio time.

Stage 2 included the month of March and the first week of April. This was the most intense period of the project. The studio teams had to finalize aspects of their designs according to the feedback they received and then move quickly to develop technical details and to make decisions on materials, systems, etc. The RTZ Final Report was limited to 44 pages, but could be supplemented by a Volume 2 with appendices, drawings, cut-sheets, etc. The teams focused on solidly addressing the ten evaluation parameters in the Final Report—a difficult task considering the page restriction. The teams also had to provide final information to the consulting students early enough to get the analyses they needed for the report. The faculty advisors also wanted to review the draft reports a week prior to submission so that the teams could make edits. The timeline for all of this was very tight. All teams that submitted a Final Report were invited to the RTZ juried event at the National Renewable Energy Laboratory in Colorado.

Figure 3: A Ball State team at the RTZ poster session.

Stage 3 involved the three weeks after submission of the Final Report. During that time, the teams prepared for the event by creating 20-minute PowerPoint presentations, rehearsing their presentations, creating a poster, and building physical scale models. Models were not required as part of the RTZ event, but were allowed. The teams believed that physical models, although difficult to transport, could highlight elements of the designs during the presentations and the poster session. Few teams brought models to Colorado and the models our teams brought attracted some positive attention.

The Colorado event was a highlight of the semester and the RTZ process. The students were very excited to be there, to share their work, and to compete with other schools. NREL hosted a very nice student-centered event that brought an impressive level of seriousness and scrutiny to the design ideas and solutions in the project proposals. After returning to Indiana, the team presentations were repeated for department faculty as a final academic review for the semester. This review had an architectural rather than a building science and constructability focus.

Graduate "energy" elective (Arch 632). Arch 632, High-Performance Buildings, is a graduate course in the Masters of Architecture curriculum. It is offered on a regular basis and fulfills a role as a NAAB Realm B: Building Practices, Technical Skills and Knowledge elective. The specific content of this course varies from semester to semester (having, in the past, dealt with net-zero energy office design, energy simulations, carbon-neutral building design, for example). In spring of 2017 Arch 632 focused on energy modeling in direct support of the Race to Zero competition. The six students enrolled in this course acted as consultants to the Race to Zero studio teams—with five of the six also enrolled in Arch 501 studio. During the semester, this class learned how to use (at least at a rudimentary level) REM/Rate, Climate Consultant, HEED, BEopt, and WuFi (well almost on this one). A major focus was on the use of REM/Rate to obtain and improve a HERS rating—a requirement of the competition. An important secondary focus was the use of BEopt to select a rational mix of design strategies. HEED was used by one team to explore passive survivability. Student work developed over the course of the semester is available at: http://wtgzik.pairserver.com/courses/632s17/work.htm

Graduate "green" elective (Arch 633). Arch 633, Advanced Technologies for Green Building, is also a graduate course in the Masters of Architecture curriculum. It is offered on a regular basis and it too fulfills a role as a NAAB Realm B: Building Practices, Technical Skills and Knowledge elective. The specific content of this course varies from semester to semester (having, in the past, dealt with the LEED BD&C rating system, LEED EBOM, and the Well Building Standard, for example). In spring of 2017 Arch 632 focused on the application of LEED for Homes to each of the Ball State RTZ projects—acting in a consultancy role. Six students were enrolled in spring 2017 (only one of whom was on a studio team). Student work from this course is available at: http://wtgzik.pairserver.com/courses/633s17/work.htm

Construction management students (CM). Two Construction Management students enrolled in an independent studies course as a means of participating in the Race to Zero competition. This involvement with architecture students mirrored a similar collaboration several years ago on the Ball State Solar Decathlon project. The main focus of the CM students was cost estimating, which was a substantially arduous task in support of four teams with changing design solutions.

Student project outcomes. Ball State teams participated in all four RTZ housing contests. Below are short summaries of each project and a technical visual that highlights outcomes of the integrated design process.

The Attached Housing (AH) team focused on modular, prefabricated duplex-style units designed to be connected and arranged in a variety of different ways to suit specific site context, solar orientation, and community engagement considerations. The chosen site was in downtown Indianapolis, IN in Climate Zone 5. The duplex consisted of 1-bedroom and 2-bedroom units on two levels. Façade materials and details were designed to be regionally appropriate while adaptable to other geographic locations. A rainwater harvesting system addressed run-off, landscape irrigation, and graywater use. The envelope design included R-42 SIP walls, an R-50 SIP roof, and U-0.15 high-performance windows. Mechanical systems included tankless, on-demand hot water heaters; ductless mini-split heat pumps with multiple terminal units; and energy recovery ventilators. The roof accommodates a 10 kW fixed-panel, monocrystalline PV array that produces more electricity than the units are predicted to use on an annual basis. The HERS rating was 38 without PV and -5 with PV. See Figure 4 for a diagrammatic illustration of the team's PV system design.

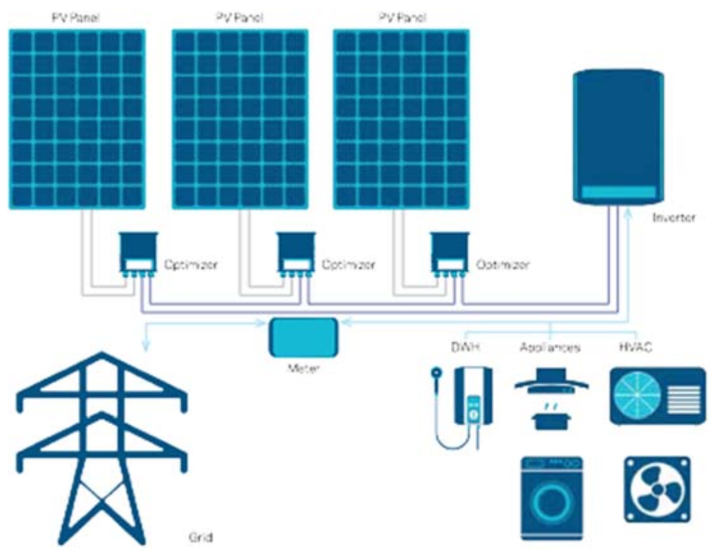

Figure 4: Attached Housing proposal for PV and building electrical components.

The Small Multifamily (SMF) team focused on a contemporary adaptation of the historic Boston triple-decker housing typology. The chosen site was an infill lot in the existing Jamaica Plain neighborhood of Boston, MA in Climate Zone 5. The building consisted of two 1-bedroom, 2-bedroom, and 3-bedroom units (a total of 6 units). The 1 and 2-bedroom units were designed with lofted bedrooms on two levels and the 3-bedroom units were at ground level for families with children. The wood façade cladding references the traditional clapboard and shingle siding in the neighborhood. Low-VOC materials were intended to enhance indoor air quality (IAQ) and to appeal to buyers with an interest in green and healthy living. All units were designed for cross ventilation with the lofted units designed for stack ventilation through a roof monitor. Glazing was carefully arranged to ensure optimal energy performance and daylighting. Insulated concrete form (ICF) construction was used throughout, which allowed for a perfect exterior wall (air, vapor, water, and thermal control in a monolithic assembly) and acoustical/fire separation between units. The envelope design included R-30 ICF walls, an R-60 ICF roof, and U-0.17 high-performance windows. Mechanical systems included tankless, on-demand hot water heaters; ducted air-source heat pumps, and heat recovery ventilators in each unit. The roof accommodates a 32 kW fixed-panel, monocrystalline PV array that produces as much electricity as the units are predicted to use on an annual basis. Energy performance was HERS 39 without PV and HERS 0 with PV. See Figure 5 for an illustration of the team's ICF roof/wall assembly detail.

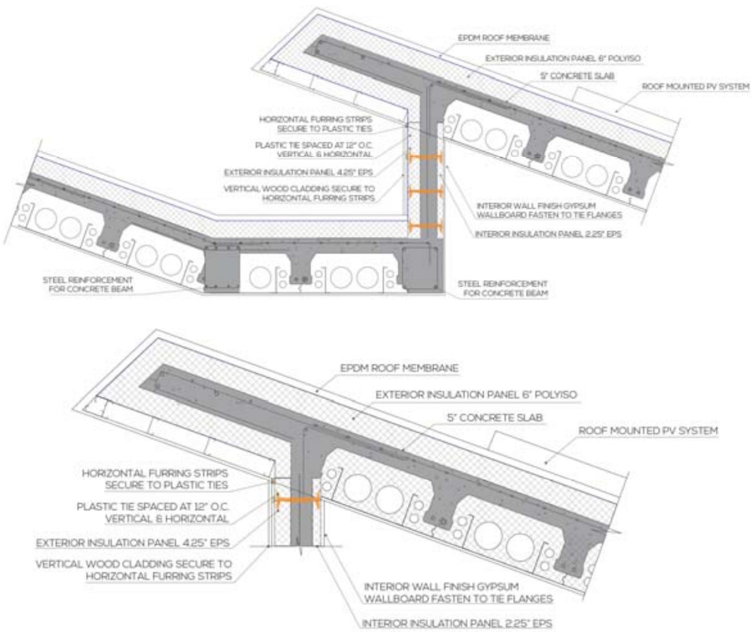

Figure 5: Small Multifamily proposal for ICF roof/wall assembly details.

The Urban Single-Family (USF) team focused on urban living and new infill housing as a catalyst for neighborhood redevelopment. The chosen site was a lot in the existing Phoenix Hill neighborhood of Louisville, KY in Climate Zone 4. The 1,900 SF single-family house had 3 bedrooms and 2.5 baths on 2 levels. The house was designed to be visually responsive to the neighborhood context. An "environmental mediator" was designed as a façade treatment that responds to solar orientation and shading needs. To address the tight urban site a second-story porch allows owners to be a part of the street while still having privacy. A second-story living space gives the public areas of the house a multi-story connection and takes advantage of the roof pitch. The envelope design included R-36 SIP walls, an R-53 SIP roof, and U-0.20 high-performance windows. Mechanical systems included a tankless, on-demand hot water heater, a ducted air-source heat pump, and an energy recovery ventilator. The roof accommodates a 9.2 kW fixed-panel, monocrystalline PV array that produces more electricity than the house is predicted to use on an annual basis. Energy performance was HERS 38 without PV and HERS -16 with PV. See Figure 6 for an illustration of the team's plumbing fixture, piping, and riser design—developed in response to competition requirements to comply with DOE Zero Energy Ready Homes performance targets.

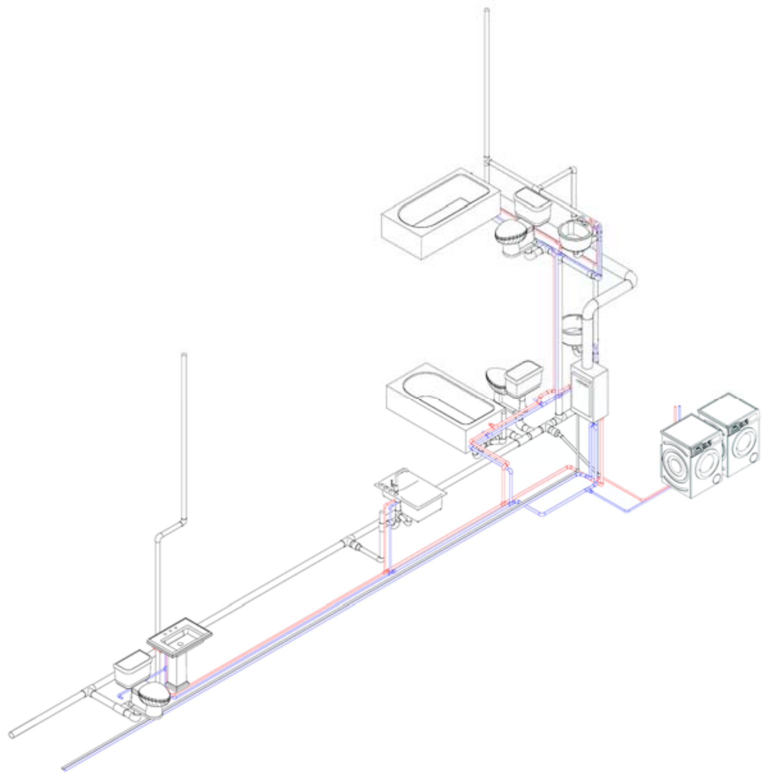

Figure 6: Urban Single-Family plumbing diagram.

The Suburban Single-Family (SSF) team focused on developing an existing developer spec home design into a Zero Energy Ready Home for young couples or retirees. The chosen site was an infill lot in an established neighborhood in Bloomington, IN in Climate Zone 4. The 1,600 SF single-family house had 2 bedrooms and 2.5 baths on one level. The house was designed for an existing site with limited buildable area and was to be built by a developer using in-house construction crews. One feature of the design was optimized connections with the exterior through the use of a screen porch breezeway and a large exterior deck for outdoor living. The envelope design included R-36 stud walls with cavity and continuous insulation, an R-60 roof, and U-0.12 high-performance windows. Mechanical systems included a tankless, on-demand hot water heater; 2 ducted mini-split heat pumps; and an energy recovery ventilator. Performance analysis included calculating the percentage of the year that the house could be operated passively without active systems. The roof accommodates a 6 kW fixed-panel, monocrystalline PV array that produces more electricity than the house is predicted to use on an annual basis. Energy performance was HERS 41 without PV and HERS -3 with PV. See Figure 7 for an illustration of the team's mechanical system design.

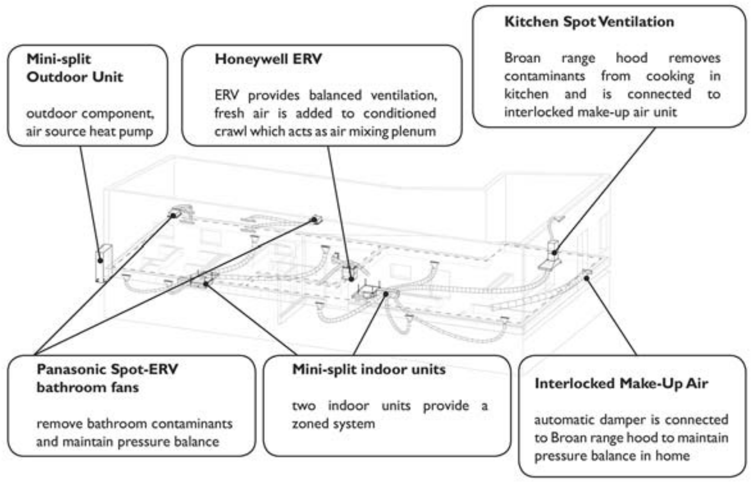

Figure 7: Suburban Single-Family mechanical system design proposal.

CONCLUSIONS

Outcomes. 2017 was Ball State's first experience with the Race to Zero (RTZ) competition, and we entered not knowing exactly what to expect. The teams produced quality work through a collaborative integrated design process. Several students even said that it was their favorite design studio thus far. Others noted how much they learned going through the process. The students came away from the experience with a positive impression of RTZ. At the RTZ event in Colorado, the SSF team received the first place prize in the suburban single family category—interestingly, this was the team that worked semi-independently.

The students were pleased with their participation in the Race to Zero. They even praised the building science training modules as being quite useful—an outcome that links directly back to an objective of the competition. The faculty were pleased with what the RTZ brought to the studio and lecture classroom. Most industry partners seemed very happy to participate and share their expertise. After the fact, it became clear that the Ball State administration was pleased with involvement with the RTZ—the student teams have been featured in several university presentations.

Challenges. There were a few challenges with our RTZ experience. First, it was challenging to come up with the money for the entry fees. This may be one reason that few schools enter all four contests. The RTZ event in Colorado is fantastic, but it was also difficult to fund 10 students and several faculty to travel out of state. The funding challenges were overcome with institutional support; but they were a concern nevertheless. The competition schedule technically begins in June, but this doesn't align with many academic calendars, particularly if you only have one semester in which to run the competition through a course. The result for us was a 12-week sprint to do what some teams did in 6-7 months.

Lessons learned. Overall, Ball State had an extremely positive experience with the 2017 Race to Zero competition. In fact, we plan to enter the competition again in 2018. It is useful, however, to highlight a number of lessons learned in the process, which may help ensure future success for Ball State and other university teams.

Ball State ran the competition primarily through a design studio. As far as we could ascertain, this was not common among other teams. Many teams engaged the RTZ as an independent project that students worked on in their spare time outside of class. An architectural design studio required that students conceive and develop compelling architectural design concepts for their projects. However, architectural design was just one of ten evaluation parameters for the RTZ. More time spent on concept generation meant less time available for design development and technical details.

Design professionals understand well the importance of communication among team members. Design students, who all-to-often work independently, do not have clear communication protocols or habits in place to facilitate work with partners across class lines and with industry professionals. This wasn't a major problem for our teams, but there were some delays the exchange of information or feedback that could be streamlined in the future.

Our core teams had two or three members working with a larger group of consulting students and professionals. Although the teams produced an impressive body of work and submitted all materials on time, the consensus from student feedback was that the core teams were too small. The old saying "more hands make lighter work" is certainly applicable in this case.

The students did not know the exact make-up of the Race to Zero juries during the design process. The teams simply focused most on what they anticipated would be important for a winning scheme and on creating a unique identity for their schemes. The juries across the evaluation areas, however, were very diverse. Some juries focused almost entirely on constructability, while others focused on systems integration. If those aspects were not emphasized or well resolved in a proposal, students received many on-the-spot questions about their design decisions. RTZ is a design competition, but students should not count on the fact that jurors are designers or even that they are primarily concerned with design or aesthetic concerns.

The Race to Zero attracts students from engineering, construction management, architecture, and other disciplines. Some team projects were highly resolved in their systems design, some projects highly resolved in terms of their construction costs, and some projects highly resolved spatially and aesthetically. Juries tended to recognize that every team brings a different approach to the problem of net-zero-energy housing. There is no silver bullet—no one way to be successful in RTZ. A successful project seemed to be one that made a strong case that the design process was well considered, rigorous, and had some unique focus.

Finally, there is an adage that "need to know" can enhance learning outcomes. The Race to Zero provides a great vehicle where the need to know building science can be felt by participants throughout the design process. Count this as a success of the Race to Zero.

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2016-2017 Race to Zero Competition: A Case Study Design for Zero Energy Ready Townhomes

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ABSTRACT

Since 2014, faculty and staff of the Pennsylvania Housing Research Center (PHRC) and the Energy Efficient Housing Research Group (EEHR) at Penn State have collaborated to support student design teams for the Department of Energy (DOE) Race to Zero competition. This annual design competition challenges interdisciplinary undergraduate and graduate student teams to design an affordable, marketable, net zero energy ready home that meets the DOE Zero Energy Ready Home (ZERH) standard and incorporates sound building science principles. Each year of the competition, Penn State students have gone beyond baseline competition requirements to partner with a Pennsylvania-based housing organization. These partnerships have provided a real site, context, and design constraints for the students' submission and have opened the opportunities for greater community impact and industry partnerships. The 2016-2017 Penn State student team partnered with the Centre County Housing & Land Trust (CCHLT) and Ferguson Township to develop a case study design for a set of three owner-occupied townhomes within 80%-120% of the median family income in a proposed Traditional Town Development (TTD) two miles from Penn State's University Park campus. This paper describes the integrative design and decision making process by the team and the technical design of the townhomes presented at the April 2017 Race to Zero competition held in Golden, CO.

INTRODUCTION

Since 2014, faculty and staff of the Pennsylvania Housing Research Center (PHRC) and the Energy Efficient Housing Research Group (EEHR) at Penn State have collaborated to support student design teams for the Department of Energy (DOE) Race to Zero competition. This annual design competition challenges interdisciplinary undergraduate and graduate student teams to design an affordable, marketable, net zero energy ready home that meets the DOE Zero Energy Ready Home standard and incorporates sound building science principles. (NREL, 2017) Each year of the competition, Penn State students have gone beyond baseline competition requirements to partner with a Pennsylvania-based housing organization. These partnerships have provided a real site, context, and design constraints for the students' submission and have opened the opportunities for greater community impact and industry partnerships.

Building on the portfolio of iterative, climate zone-appropriate affordable housing designs across the history of Penn State's involvement in the competition, the 2016-2017 Penn State student team partnered with Ferguson Township (a township adjacent to Penn State) and the Centre County Housing & Land Trust (CCHLT) to develop a case study design for a set of three owner-occupied townhomes that are affordable to families within 80%-120% of the median family income in a proposed Traditional Town Development (TTD) two miles from Penn State's University Park campus. This case study paper will describe the integrative design and decision making process by the team and technical design of the townhomes for the 2016-2017 Penn State Race to Zero submission.

ENERGY EFFICIENT HOUSING DESIGN AT PENN STATE

Solar Decathlon (2007 & 2009)

Students and faculty at Penn State have been researching and working with energy efficient design for more a decade. Two significant projects that catalyzed and institutionalized energy efficient housing design at Penn State were the US DOE's Solar Decathlon competition entries in 2007 and 2009, each of which were utilized as precedent for the Race to Zero competition structures.

For each competition students and faculty from across the university spent two years designing an energy efficient showcase home that was fully designed and built by the students, but each competition administration structure was tailored to the student, faculty, and university needs of the given competition year. To build student, faculty, and university capacity, the 2007 'MorningStar' home competition project was kicked off by a university-wide design competition and ultimately integrated with several classes and design studios. For the 2009 competition, the 'Natural Fusion' home project was driven by the student and university knowledge and capacity built by the 2007 competition. Reflecting the overall increase in university and student capacity, work was completed primarily through an extracurricular club structure with independent study credits offered when needed, rather than being embedded and administered through classes and studios. Following these competitions, research into innovation, energy efficiency, and building science related to residential design has grown at the university.

Race to Zero (formerly Challenge Home Competition) (2014-present)

In early 2014 the Race to Zero competition (note: the competition was called the Challenge Home competition for 2014-2015) was developed by the DOE as a complementary competition to the Solar Decathlon competition. While the goal of designing highly energy efficient homes remained consistent between the two competitions, the Race to Zero competition was developed to have an increased focus on building science and market-ready housing solutions. Additionally the Race to Zero competition was developed as a paper-based competition, so teams were not required to physically build their home designs, thus lowering any associated costs with the competition and allowing more students and universities to participate. Successful homes designed for the competition must comply with the DOE's Zero Energy Ready Home program, which include:

- Qualifies for ENERGY STAR certification
- 2012 or 2015 IECC insulation levels
- HVAC and all duct systems located within the thermal boundary
- Efficient hot water delivery systems
- Qualify for EPA Indoor airPLUS certification
- A HERS score of around 50, depending on final home size, and
- Complies with the DOE Zero Energy Ready Home PV-Ready Checklist (DOE, 2014)

In addition to these technical requirements, the competition also requires the home to be affordable for the location's Median Family Income (MFI). Affordability for the competition is defined as a monthly payment of 38% of the MFI including, not only the mortgage, taxes, and insurance, but also the predicted average monthly utility cost. Finally the competition also encourages student teams to work with industry partners in their area while developing their project to better learn sustainable design and real-world practices and better prepare them for becoming future professionals in the design and construction industry.

Penn State has participated in the competition since its introduction in 2014. To enhance the experiential learning opportunity for the students, as well as to have a local impact in improving Pennsylvania's housing stock, Penn State has partnered with a Pennsylvania-based affordable housing organization each year of the competition. At a minimum the partnership is composed of a single point of contact at the organization for context, questions, and feedback, as well as a specific site or development for the proposed home design. Several partnerships have gone beyond the minimum to include written explicit expectations of the students design by the partner, one or more site visits to the location, and engaging the point of contact in one or more design charrettes.

A notable Penn State precedent competition entry was the 2014-15 competition - *Heritage Homes*. For this competition, the team partnered with the State College Community Land Trust (SCCLT) to design a net zero energy ready duplex in the State College Borough (2014-2015 Penn State Race to Zero Team, 2015). Throughout the competition year, the student team led three design charrettes with members of the SCCLT board, SCCLT homeowners, students, faculty, and staff at Penn State, and community members from around the State College area. Following the competition, the SCCLT continued to work with the Energy Efficient Housing Research group, an outreach arm of the Hamer Center for Community Design in the Penn State Stuckeman School for Architecture and Landscape Architecture, and a co-facilitator of the Race to Zero competition at Penn State to see the homes through final design and construction. The duplex construction is anticipated to be completed by July 2018 at 1394 and 1396 University Drive based primarily on the design of the student team from three years prior.

Figure 1. History of the Race to Zero Projects & Community Partners at Penn State (image credits (left to right): 2013-2014 Challenge Home team, 2014-2015 Race to Zero team, 2015-2016 Race to Zero team, 2016-2017 Race to Zero team)

Following the success of that project, the Penn State Race to Zero team was approached by the Centre County Housing & Land Trust (CCHLT) to design a case study home for a new development close to Penn State's campus. The Turnberry Development, a Traditional Town Development (TTD) located in Ferguson Township, is planned to have 891 dwelling units throughout 154 acres over 16 years.

Furthermore, Ferguson Township has a Workforce Housing Ordinance in place for this zoning designation that requires 10% of the homes constructed be affordable to owner-occupied families earning between 80% and 120% of the area median income (AMI) (Ferguson Township, 2016). Once constructed these homes would then be sold and administered as permanently affordable housing by the CCHLT.

DESIGN PROCESS

Educational Structure

Building off the lessons learned from the Solar Decathlon and each Race to Zero competition, Penn State strives to tailor each year's Race to Zero competition educational structure based upon several factors, primarily:

- student capacity (year of study, previous home design experience, etc.),
- project partner expectations (level of problem presentation detail, if it will be built, etc.), and
- faculty/staff capabilities/capacities (university classes, mentoring, etc.)

Given these factors, the 2016-2017 Penn State team was run as a student club rather than an official class for students to take. This competition structure provided the advantage of flexibility so that the project team can work through the entire academic year (rather than embedding it in a semester course). However it also provided students less incentive to participate in and follow through on the competition project.

Team Structure

The Penn State team for the 2017 Race to Zero competition was comprised of students from Architecture, Architectural Engineering, and Civil Engineering, as well as Chemical Engineering, Energy Engineering, Material Science, and Mechanical Engineering. The team was primarily made up of undergraduate students in their third or fourth year of study with some first and second-year students as well as a few graduate students. Only three students were returning from previously competing in the project.

Overall, most students had little or no experience designing or building homes. This provided both a great challenge and great opportunity to not only educate students about residential design and energy efficiency, but also gain diverse perspectives about the design of these homes.

Throughout the year-long project, the Penn State team worked to engage all interested students – regardless of background or study – in the design of the homes through an integrative design process. All team members got a say in what the homes will look like, how they function, and what technical systems are integrated into the homes. To move forward in this design process, the team leaders designated five sub-teams that would focus on primary elements of the home – Architecture, Building Envelope, Energy Analysis, Systems Integration, and Finance. The sub-teams met outside of regular team meetings for research and analysis, but most design decisions were made during weekly team meetings with members of all of the sub-teams present. Weekly team meetings were used to discuss concept goals, design decisions, and determine project timelines; these meetings were generally held during weeknight evenings lasting 1-2 hours; longer weekend worksessions were used for the team and individual sub-teams to work together on design, documentation, and analysis of the homes. These longer worksessions became essential to the completion of the project since this allowed for the project to develop holistically as students from separate sub-teams were able to ask questions and design with consideration for the entire project.

Figure 2. 2017 Penn State Race to Zero Team Design Charrette (image credit: S. Klinetob Lowe)

Community Engagement

A focus for the team was professional and community engagement. By working with a site and project so close to the University, the students were able to engage and interact with: members of the Ferguson Township Board of Supervisors; board and staff members of Centre County Housing & Land Trust (CCHLT); experienced builders, architects, and engineers; and community members from around the area. The team worked closely with Rachel Fawcett (then Executive Director of CCHLT) and Peter Buckland (Vice Chair of the Ferguson Township Board of Supervisors) to find the development, choose a housing type, determine design constraints and energy guidelines, and establish housing cost targets. Throughout the competition, the team continued to work with Peter and Rachel to develop the design and share the design with the rest of the Ferguson Township Supervisors and CCHLT board.

The Penn State team also participated in multiple outreach efforts to gain information about what local community members wanted from their homes. In December 2016, the team attended the Penn State University Sustainable Communities Collaborative Expo at the State College Borough Building, a public event showcasing community-oriented work by students of the university. At the event, students asked community members what they might change about their home and what they perceived affordable and sustainable housing to mean. The students created a large poster survey and asked passers-by to respond to the questions on the poster; the team was then able to use these responses when designing the homes. Team members also attended a work session at the Ferguson Township Municipal building regarding the development of a housing development adjacent to Turnberry Development. In both of these events, students learned about values and design features important to the community and to Ferguson Township.

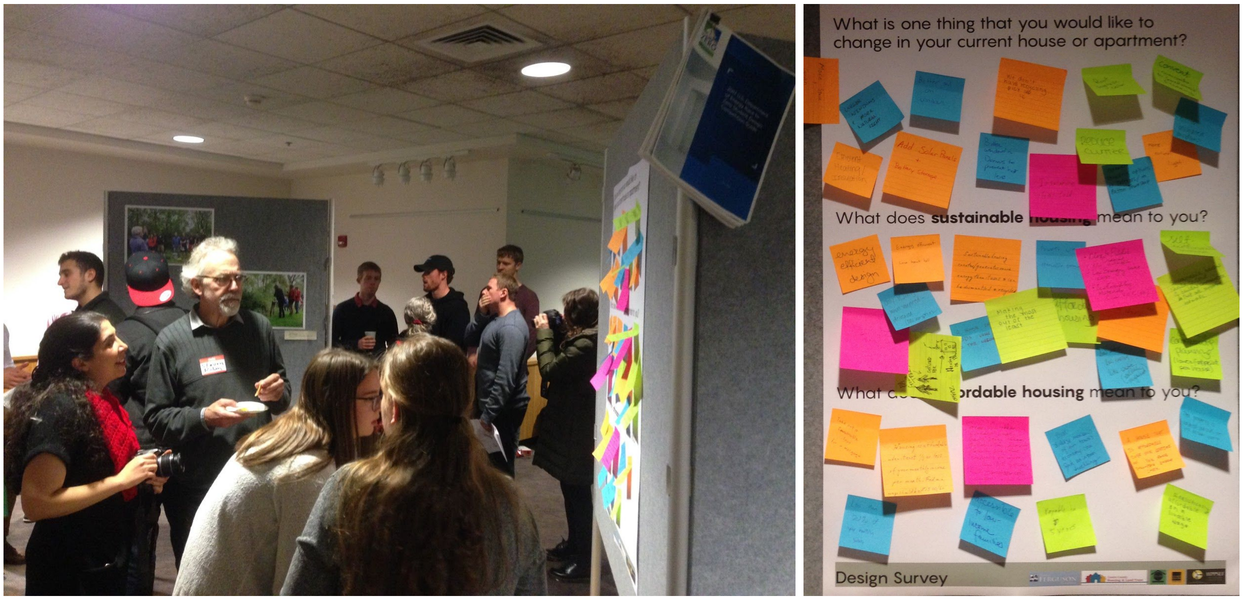

Figure 3. Team members working with community members at the Penn State Sustainable Communities Collaborative Expo (image credit: C. Hazel)

Throughout the competition, the team also engaged with many local building professionals when determining materials selection, issues of constructability, and technical design. These partnerships provide a special opportunity for students to gain valuable experience working outside of the classroom environment while expanding their personal and professional network of industry relationships. Partners included energy consultants, construction estimators, and building contractors, all with invaluable experience to help the team better understand and visualize the project.

ARCHITECTURAL DESIGN

When it came to defining a core concept to guide the design of the home, the team turned to the history of the Turnberry Development's site. During the 1970s and 80s, the site was owned by Penn State and used as a student farm. The team used this history to develop a design concept around food and agriculture. In addition to connecting to the land, the team wanted to emphasize community interaction as a key design concept.

The team explored the design and intent of the TTD and proposed an alternative site plan that took better advantage of passive solar orientation, allowed for denser development, and introduced spaces for community gardens, playgrounds, etc. as a way to encourage more community interaction and sociability within the development.

When contemplating the program of the homes, the team focused on the potential homebuyers and the existing proposed development details. The existing development plan had a mix of ten housing types in the area the team designed in, and four housing types qualified for Ferguson Township's Workforce Housing Ordinance.

The team decided to modify a proposed townhouse cluster for their project ending up with a mix of three townhomes: 20' width, 16' width, and 22' width. This type of cluster would allow for the 16' unit (the middle unit) to always qualify for the Workforce Housing Ordinance (80% AMI, 3-person household); the 20' unit could qualify for the ordinance (100% AMI, 4-person household) or be upgraded. The 22' unit would always be for families above the income qualification for the Workforce Housing Ordinance (120% AMI, 4-person household). This layout matched the Workforce Housing Ordinance that required no more than two qualified homes be adjacent to each other and required that qualified homes must have a similar exterior appearance to non-qualified homes (Ferguson Township, 2016). This design also allowed the team to spread the overall construction costs of the three-unit cluster across three different families, allowing for some units to be more affordable without sacrificing functionality or space.

In addition to meeting the Workforce Housing Ordinance design requirements, the team designed the homes to require as little energy as possible while maintaining some freedom in the placement of the homes. This was the first year a Penn State Race to Zero team designed homes for a development and therefore had to think about how changes in orientation could impact the energy usage of the homes. In the re-development of the site plan, the team simplified the design into a strict grid pattern, limiting orientations to East-West. The team decided on this orientation primarily due to the long and narrow layout of the homes (between 16'-22' width and 32' depth). The roofs were designed with the longest plane facing south in order to maximize solar potential for solar photovoltaic panels, however this did limit the amount of passive solar heat the homes could receive. Due to this constraint the team designed the interior layout around the limited direct natural daylight. The kitchen served as the center of the home, reinforcing the team's concept of food and agriculture; the east side of the home contained the breakfast and dining room area; the team expected this area to be where the family gathers for breakfast and kids finish their homework due for that day. The living room is placed in the west side of the first floor where sun will reach in for the last few hours of the day while the family watches a TV show or plays a game. The house also extends into a large backyard and patio to be used for gardening and hosting barbeques. The second floor of each home varies slightly depending on the size and number of bedrooms, but all three floor plans brings the occupants to a central hallway with a bathroom and laundry closet in the center of the second floor. Bedrooms are located at the front and rear end of the homes, three bedrooms in both the 20' unit and the 22' unit, but only two bedrooms in the 16' unit.

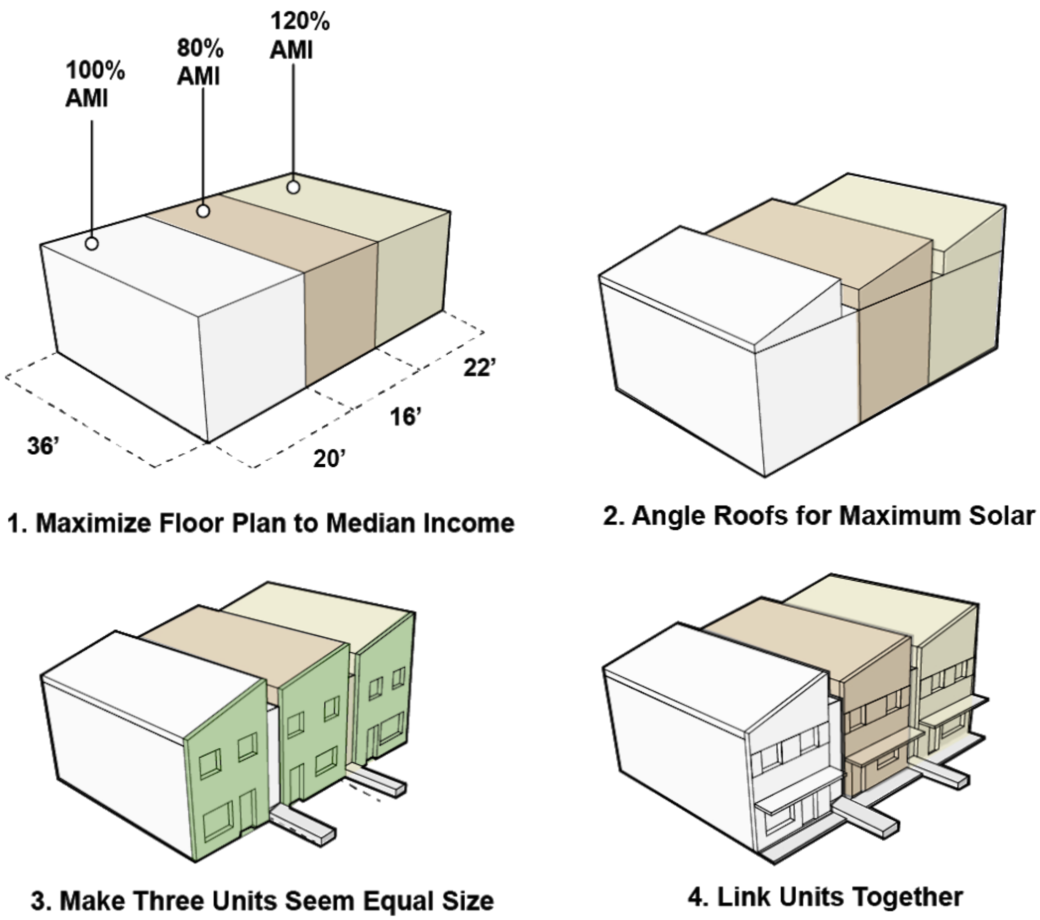

Figure 4. Design Diagrams for 2017 Penn State Race to Zero home (image credit: 2016-2017 Race to Zero team)

Figure 5. 2017 Penn State Race to Zero competition design exterior rendering (image credit: 2016-2017 Race to Zero team)

TECHNICAL DESIGN: BUILDING ENVELOPE

The building envelope is one of the key features to creating a high-performance home, however the Penn State team considered a lot more than just the R-value when designing the home's envelope. The key areas focused on were constructability, affordability, durability, and the properties of the materials used. What would be the point of a wall that reduces a home's carbon footprint, when the material in the wall has extremely high embodied energy, i.e., the energy required to manufacture and move the material?

The first step for the design team was to determine the air/moisture and thermal boundaries of the home. This continuous boundary provided the team with the extents of the conditioned space and forced the envelope team to understand what kind of materials would be needed to provide a high-performance building envelope. In order to design the best envelope for the home that would meet the criteria, extensive research was done into many wall systems and many different materials, with a particular focus on wall systems with proven building science performance properties. BEopt was used to optimize the insulation levels, price, and energy savings of the proposed envelope designs. After that, the top choices were evaluated using weighted decision matrices to settle on a final design. This process allowed the team to consider the many important criteria simultaneously and in a relatively unbiased way.

The final wall design used an Optimum Value Engineered wood stud structure (2x6 wood stud, 24" O.C.) with dense packed cellulose insulation, ½" ZIP panel sheathing, 4" Roxul Comfortboard mineral wool insulation, and LP Smartside engineered wood siding to provide a more natural aesthetic to the homes. Materials were chosen that would be available in the State College area, are easy to build with, and lower the overall embodied energy and maintenance of the homes.

The foundation is a Frost Protected Shallow Foundation wrapped in 2" of Extruded Polystyrene (XPS) insulation; energy modeling showed that R-10 insulation would be ideal for the homes' underslab insulation, so as to lower cost and reduce potential future maintenance, the team decide to use XPS insulation despite its high embodied energy. The roof is made up of a raised heel truss to prevent wind washing of the insulation with R-60 blown-in cellulose insulation.

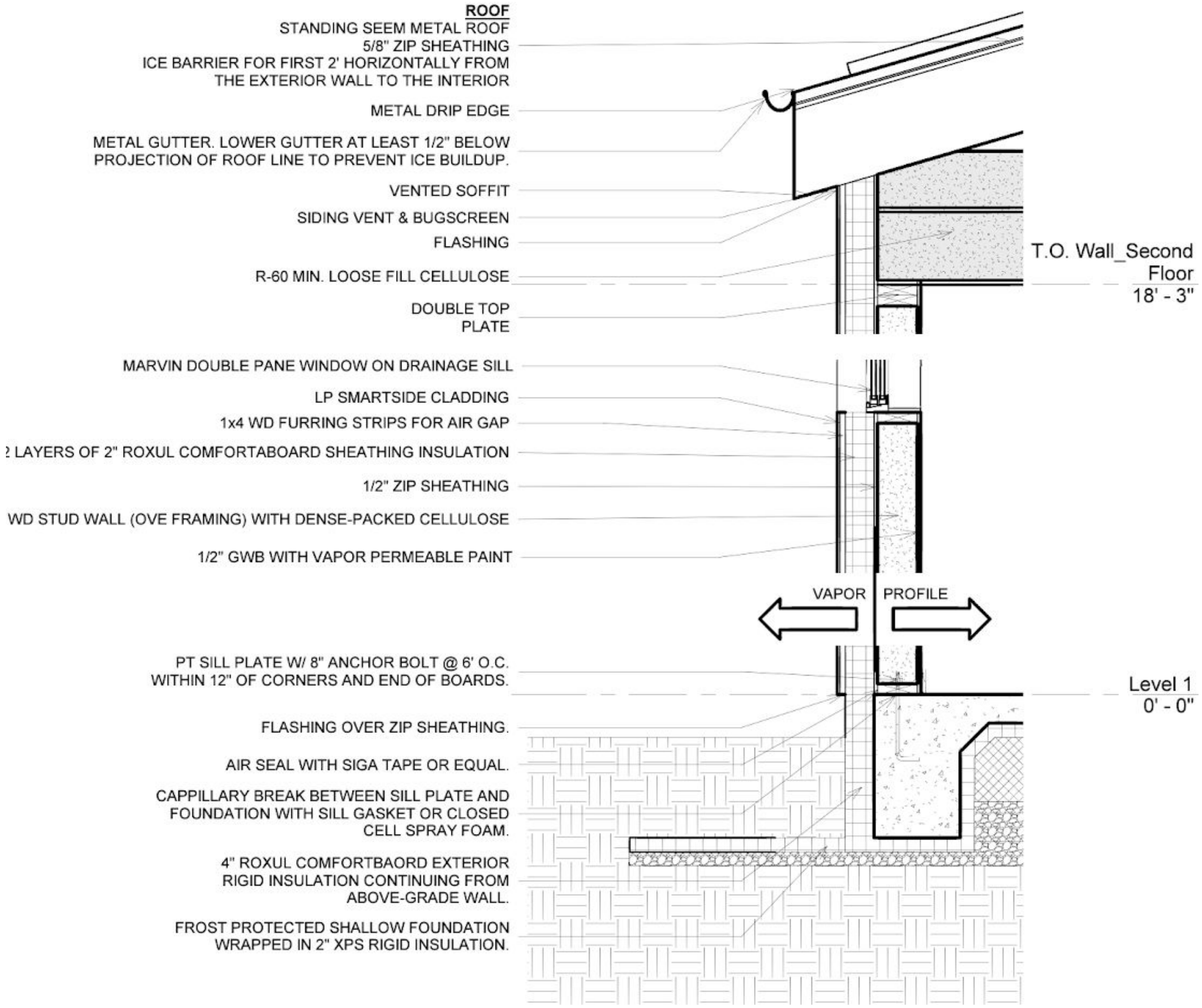

Figure 6. Full-wall section of the 2017 Penn State Race to Zero home (image credit: 2016-2017 Race to Zero team)

TECHNICAL DESIGN: BUILDING SYSTEMS

When choosing the proper HVAC system the team wanted a system that was affordable, easily implemented into the homes, and would evenly and adequately condition and ventilate the low-load homes. In keeping with the team's design concept of low energy usage and low embodied energy, the team focused research into heat pump technologies for conditioning the homes. Much of the research done by the HVAC and systems integration group was around the distribution methods for heating and cooling the homes. Initial research showed potential for high-velocity ducted systems, but the team ultimately felt that the potential energy savings were not yet proven and would not be worth the additional cost and noise of the system. The team ultimately chose a ducted mini-split system with one outdoor unit and two indoor units per home. The ducted system was chosen as a way to more evenly distribute conditioned air throughout the homes despite the slight reduction in performance. Indoor units were placed near the center of the home with ductwork kept to a minimum and branching out to spaces along the front and rear walls. Because of the performance of the thermal envelope, the team was able to use small load space conditioning systems, a single 22 kBTU outdoor unit with two 18 kBTU indoor units to distribute the air.

The homes are designed to minimize air leakage, so mechanical ventilation is required. To ensure fresh air without losing energy, the team decided to use a balanced mechanical ventilation system with a Heat Recovery Ventilator (HRV) and connect it with the space conditioning ductwork.

Similar to the HVAC system, the building's plumbing system is designed to minimize the distance that heated water needs to travel until it reaches a fixture. The homes are designed to centralize all water utilities in the middle of each unit in order to reduce the length of water lines as much as possible. On the first floor, the kitchen is placed adjacent to or near the bathroom in each of the units, and the second floor bathrooms are located above the first floor bathrooms. After reducing the the distances between the hot water supply and the water fixtures, the team had to determine the piping supply system to minimize standing water within the lines. For cost and durability reasons, the team chose Pex plastic piping. The team calculated water volume for both a homerun layout and a remote manifold layout. After comparing the two systems in each unit, it was found that, while both held very little water in the lines, the remote manifold layout performed slightly better and required less piping. Because of that, the team chose to use pre-insulated Pex pipes in a remote manifold system layout. All fixtures for the home are WaterSense certified; the team also chose to use a GE Geospring Heat Pump Water Heater to provide hot water to the homes.

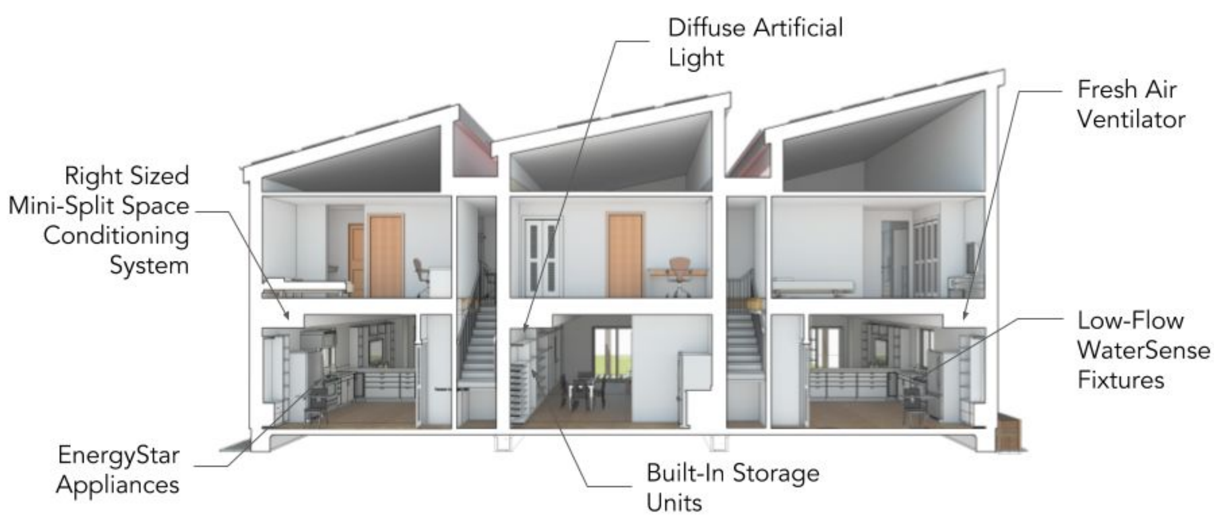

Figure 7. Energy efficiency features of the 2016-2017 Race to Zero Home design (image credit: 2016-2017 Race to Zero team)

ENERGY ANALYSIS

The homes are designed to reduce as much energy as possible before using renewable energy systems to provide the energy difference to get to zero. Through an iterative design process where team members would design building massing and layout then test the designs through multiple energy analysis softwares, the team was able to design a set of homes that reduced overall usage by over a third compared to a similar set of new homes built to the 2009 International Energy Conservation Code standards, the energy code adopted in Pennsylvania at the time of design.

To reach net-zero energy, each home is designed to hold solar photovoltaic panels proportional to the energy load. Through working with one of the team's industry partners, Envinity Inc., the team chose to use SunPower X-Series panels with microinverters; some shading occurs during winter months, so the microinverters were chosen to keep some panels operational throughout the entire year. Projected energy usage per unit was determined from REM/Rate, resulting in 21 panels for the 16' unit, 24 for the 20' unit, and 28 for the 22' unit. The price of the system ranged from \$25,000-\$34,000 per home, but that cost would be included into the home's construction cost and therefore added to the mortgage of the home. Offsetting the energy costs through solar photovoltaic panels would save the homeowner around \$1,200 per year meaning the panels would be a net-positive investment within the 30-year mortgage.

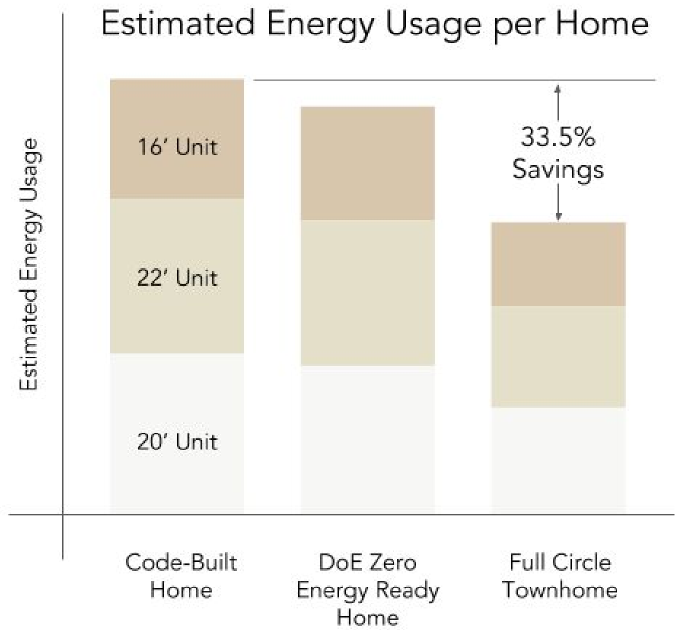

Figure 8. Typical energy savings of the Penn State Race to Zero homes (image credit: 2016-2017 Race to Zero team)

AFFORDABILITY

In addition to technical requirements, the competition requires the home to be affordable for the location's Median Family Income (MFI). Affordability for the competition is defined as a monthly payment of 38% of the MFI including, not only the mortgage, taxes, and insurance, but also the predicted average monthly utility cost. The competition also required a household debt value of 0.5% MFI to be included in the 38% affordability calculation.

The team designed the 16' unit for a home for a target MFI of $73,600 for a family of four. Figure 9 provides the financial analysis for each townhome unit.

The team designed the 16' and 20' units to qualify for Ferguson Township's Workforce Housing Ordinance, and the 22' unit as a market rate unit. As such the 2-bedroom 16' unit was designed for a 3-person household at 80% MFI, or a target income of $53,050, and the 3-bedroom 20' unit for a 4-person household at 100% MFI, or a target income of $73,600. The 22' unit would then be for 4-person families above the income qualification for the Ordinance at 120%+ AMI, or greater than or equal to a family income of $88,320.

Figure 9 shows the financial analysis for each townhome and its calculated debt to income ratio for each unit.

Financial Analysis - Comparison				
	16' Unit	20' Unit	22' Unit	Original
Total Construction Cost	$143,982	$191,748	$212,247	$182,659
Total Home Cost	$205,159	$309,626	$336,205	$283,663
Targeted Family Income	$53,050	$73,600	$88,320	$73,600
Monthly Household Debt (0.5% MFI)	$265	$368	$368	$368
Operations and Maintenance Costs	$196	$196	$196	$196
Monthly Utility Costs	$49	$49	$49	$49
Property Tax	$214	$323	$350	$295
Insurance	$79	$79	$79	$79
Mortgage Payment	$832	$1255	$1363	$1150
Calculated Debt to Income ratio(%)	37	37	34	35
Total Monthly Debt	$1,635	$2,270	$2,479	$2,137

Figure 9. Financial Analysis of Each Townhome Unit (image credit: 2016-2017 Race to Zero team)

CONCLUSIONS

Building on the portfolio of iterative, climate zone-appropriate affordable housing designs across the history of Penn State's involvement in the US DOE Race to Zero competition, the 2016-2017 Penn State student team partnered with Ferguson Township and the Centre County Housing & Land Trust to develop a case study design for a set of three affordable owner-occupied townhomes.

The townhome designs met the Zero Energy Ready Home standard and featured a high performance dense pack cellulose with mineral wool continuous insulation envelope with proven building science performance properties and low-embodied energy materials, a ducted minisplit space conditioning system connected to a balanced mechanical ventilation system with an HRV, and solar photovoltaic systems sized for 100% onsite energy offset.

Further the architectural design of seamlessly integrating multiple size units creatively met the design and spacing requirements set forth by Ferguson Township's Workforce Housing Ordinance. The design also met the competition's affordability requirement (final payment of 38% of the debt to income ratio for the area MFI) and the Workforce Housing Ordinance affordability requirement (affordable for families within 80%-120% of the median family income.)

ACKNOWLEDGMENTS

We would like to thank the students, industry partners, and Penn State faculty that have been involved with the Race to Zero competition at Penn State and have helped to make it so successful. Additionally, we would like to thank the Pennsylvania Housing Research Center, the Energy Efficient Housing Research Group and Hamer Center for Community Design, the Institute for Energy and the Environment at Penn State, the Penn State Sustainability Institute, the Penn State College of Arts and Architecture, and the West Penn Power Sustainable Energy Fund.

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Measuring Sustainability and Resilience Tradeoffs across Post-Disaster Temporary Housing

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ABSTRACT

The present research began with searching for a solution to temporary housing that residents can receive quicker with an easier transition into permanent housing allowing for better overall community recovery. A framework was developed that includes three key inputs that feed into an integrated sustainability and resilience evaluation model that outputs tradeoffs between temporary housing options for a household. The three inputs include (1) the disaster scenario which describes the type of hazard, and the level of damage to the pre-disaster home, (2) a description of the particular household in need of temporary housing, and (3) the types of temporary housing options to be evaluated. The framework is exemplified through a hurricane disaster causing moderate damage to the pre-disaster homes of the households being considered. The tradeoffs for temporary housing are compared for two different households who vary significantly based on perceived social vulnerability. Common and innovative temporary housing options are considered in the examples, including manufactured homes, RAPIDO program units, shelter at home programs, and hotel stays. The integrated sustainability and resilience evaluation model measures eight quantitative qualities of the temporary housing units that collectively formulate a quality of life index. The eight qualities include adaptability, customizability, local economy promotion, health impacts, environmental impacts, financial cost, structural integrity, and hazard vulnerability. The quantities are assigned weights based on priorities and needs of the household occupying the temporary housing unit. The temporary housing option resulting with the highest quality of life index is recommended to the household.

INTRODUCTION

Billion dollar disasters caused by extreme weather events are occurring at an increasing rate, with this rate expected to continue increasing. The National Oceanic and Atmospheric Association (NOAA) has reported over 117 billion dollar disasters since 2005 (NOAA, 2017). The increase in disasters is attributed to climate change, population growth, urbanization, and aging infrastructure (Theis, 2012). These events cause widespread dislocation exacerbating existing issues with housing, including post-disaster temporary housing.

Disaster recovery occurs in four stages: planning, mitigation, response, and recovery. Planning and mitigations take place before a disaster, and response and recovery occur post-disaster. Post-disaster housing is considered to take place in four, albeit nonlinear and overlapping, stages as well, and span response and recovery. These four stages include emergency shelter, temporary shelter, temporary housing, and permanent housing (Quarantelli, 1982). The Federal Emergency Management Agency (FEMA) designs their housing recovery programs around the following timeline and descriptions (U.S. Senate, 2009). Emergency shelter is the phase immediately following the disaster lasting for approximately two weeks. Temporary shelter begins two weeks post-disaster and spans up to three months, when temporary housing can be provided. Temporary housing lasts anywhere from 3 to 18 months, and is intended to get displaced households back into their pre-disaster routine. Permanent housing follows temporary housing and becomes the long-term housing solution post-disaster. Based on current FEMA housing recovery programs, temporary housing is expected to last up to 18 months. It has, however, lasted significantly longer in many of the billion dollar disasters that have occurred since 2005. Indeed, after Hurricane Katrina, the final temporary housing unit left New Orleans six years after the storm hit southern Louisiana (Muskal, 2012). Many of the physical structures used during the temporary housing phase are not designed to last these long periods of time, particularly when considering structural integrity of the unit, and well-being of the occupants.

Disparities in timing, quality, and location of temporary housing have been observed after the past decade of disasters (Sutley and Hamideh, 2017). The specific needs of socially vulnerable households are often overlooked in the existing recovery programs: most live in hazard prone areas, have lower quality housing construction, live in poorly built neighborhoods, are renters (and therefore have less control over dislocation decisions, as well as not applicable for recovery funds), have lower incomes, savings, and often do not have insurance, thus further hindering households' abilities to recover (Kamel and Loukaitou-Sideris, 2004; Sutley and Hamideh, 2017). To receive certain types of aid after a disaster, specific criteria must be met and losses must be proven. Oftentimes, low income, and racial and ethnic minority households do not have enough possessions pre-disaster to demonstrate substantial loss caused by the disaster or the required paperwork demonstrating ownership of their home, thus having those with higher property values receiving more aid by proving greater losses (Van Zandt and Sloan, 2017). Vulnerable populations, specifically low-income households, who experience issues receiving financial aid recover slower as a direct result (Bolin, 1991; Kamel and Loukaitou-Sideris, 2004).

Following the disparities in distribution and timing of temporary housing after Hurricane Katrina, and the timeline for temporary housing observed after 2016 disasters, particularly the Louisiana floods and Hurricane Matthew, further research on temporary housing is a necessity. The present research provides a new integrated sustainability and resilience evaluation model applied to a selection of the existing types of temporary housing units. The model is designed at the household-level taking into account the individual household's needs and preferences. The model includes three inputs specifying the disaster type, the household, and the types of temporary housing available. The model includes a process for measuring sustainability and resilience qualities of temporary housing, including adaptability, customizability, local economy promotion, health impacts, environmental impacts, financial cost, structural integrity, and hazard vulnerability. These qualities are used to formulate a quality of life index. Given a disaster, a particular household, and the available temporary housing options, the integrated model will generate tradeoffs across qualities based on household preferences, and the quality of life index.

TEMPORARY HOUSING EVALUATION FRAMEWORK

Four types of temporary housing are investigated here: FEMA provided-manufactured homes, RAPIDO program units, shelter at home programs, and hotel stays. In order to properly assess temporary housing, the framework in Figure 1 was developed which requires three crucial inputs. First, the disaster scenario defines the type of hazard, and the level of damage to the pre-disaster home. Second, a household description details the particular household being considered, including their family size, economic status, ethnicity, and insurance coverage. Third, the types of temporary housing to be evaluated are input. All inputs feed into an integrated sustainability and resilience evaluation model comprised of eight qualities of temporary housing and its accompanying program. The qualities, shown in Figure 2, were chosen based on common themes observed in the literature, and fall under resilience, sustainability, or both. The qualities are defined and accounted for across each type of temporary housing, and assigned a value based on specific measurement criteria. These values are normalized and summed for an overall quality of life index. The following subsections detail the quantification of each quality followed by the formulation of the quality of life index.

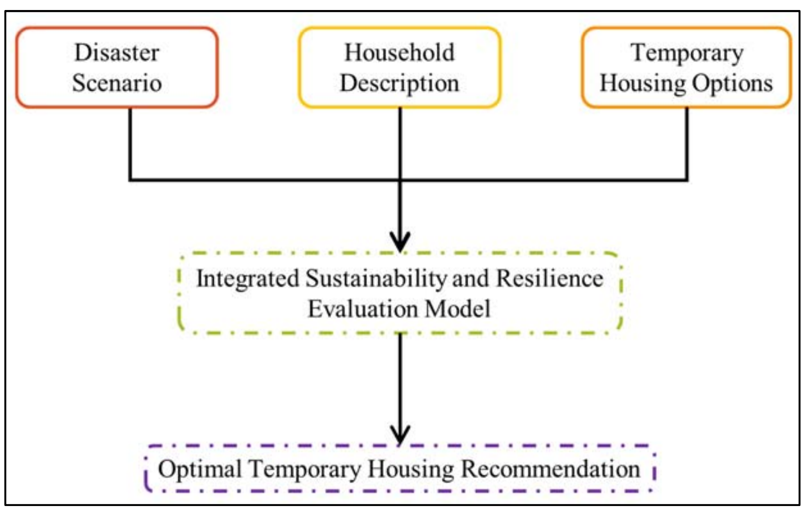

Figure 1. Temporary Housing Evaluation Framework

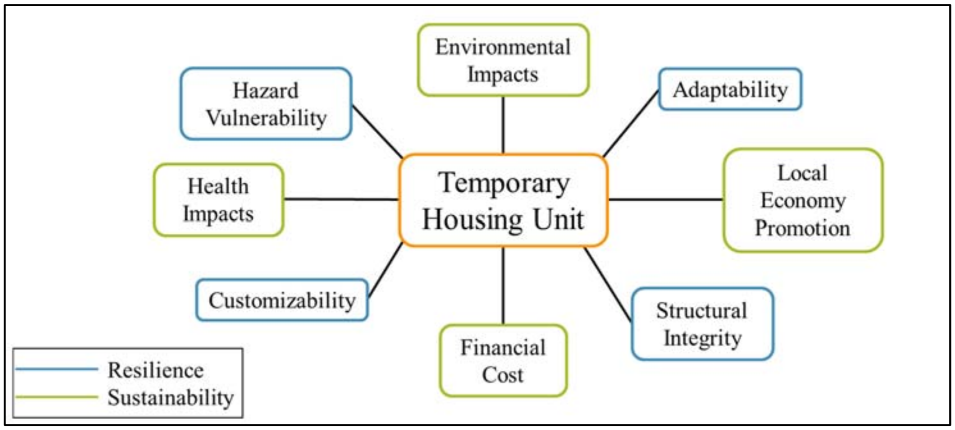

Figure 2. Temporary Housing Qualities

A systematic analysis of the literature was performed to extract qualitative and quantitative experiences of households going through post-disaster temporary housing. Table 1 provides the findings from the exhaustive review used to formulate the eight qualities depicted in Figure 2.

Table 1. Household Experiences in Temporary Housing

Temporary Housing Unit	Quality Metric	Information	Source
FEMA manufactured units	Accessibility	Group sites inaccessible or isolated from other community sectors made everyday tasks (grocery shopping, laundry, and commuting to work and school) almost impossible	Smith, 2017
FEMA manufactured units	Accessibility	One group site was located in Baker, Louisiana 91 miles northwest of New Orleans after Katrina	Levine et al., 2007
FEMA manufactured units	Customizability	Interior and exterior walls could not be painted; locations and layouts could not be specified	Verderber, 2008
FEMA manufactured units	Customizability	Residents could face legal charges if they tried to change any part of the unit	Verderber, 2008
FEMA manufactured units	Health Impacts	Domestic violence, divorce rate, depression, anxiety, sleep disorders, hypervigilance, flashbacks, and suicide rates were all observed to increase	Verderber, 2008
FEMA manufactured units	Health Impacts	Children showed signs of regressive behaviors, nightmares, increased aggression, social withdrawal and isolation, nutrition decline, and fear of darkness.	Verderber, 2008
FEMA manufactured units	Health Impacts	Elderly experienced sleep disorders, memory loss, disorientation, loss of appetite, overeating, and inability to concentrate	Verderber, 2008
FEMA manufactured	Health Impacts	50% of group site residents met criteria for major depressive disorder	Verderber, 2008

units			
FEMA manufactured units	Health Impacts	15 times as many suicides and 70 times as many suicide attempts than the Louisiana state average from those living in group sites	Verderber, 2008
RAPIDO units	Adaptability	Consists of a temporary housing “CORE” that families move into a disaster that can be expanded to create larger, permanent homes later	Morales-Diaz, 2016
RAPIDO units	Customizability	Households meet one on one with designers to select a floorplan that best meet their needs and lifestyles	Morales-Diaz, 2016
RAPIDO units	Hazard Vulnerability	After the additions, families have a permanent home that surpasses the structural integrity and safety of pre-disaster home, thus preparing for future disasters	Morales-Diaz, 2016
RAPIDO units	Customizability	Residents can install the CORE on pre-disaster property or relocate out of the floodplain	Zandt and Womeldurf, 2017
RAPIDO units	Local Economy Promotion	Keeping residents on their property and in the community help fulfill their everyday needs while building their community back together	Morales-Diaz, 2016
RAPIDO units	Local Economy Promotion	Residents can be employed as transporters and builders with both skilled and unskilled labor to slowly restore the local construction economy	Morales-Diaz, 2016
RAPIDO units	Local Economy Promotion	Purchasing materials from local suppliers also kept funds circulating in the community	Morales-Diaz, 2016
RAPIDO units	Local Economy Promotion	RAPIDO allows for funds generally spent on federal administration and implementation to be used for community recovery by putting funds back into the residents’ pockets	Morales-Diaz, 2016
FEMA manufactured units	Financial Cost	The cost of installing a FEMA mobile unit on private property was reported as $129,000: $62,500 upfront cost for mobile home; $23,000 for installation; $15,400 for maintenance; $5,000 for transportation; and $23,000 for administrative overhead cost	Allen, 2016
FEMA manufactured units	Financial Cost	The total cost for installation in a pre-existing commercial mobile home park reportedly cost FEMA $149,000	Allen, 2016
Hotel Stays	Health Impacts	Children staying in hotels were having a hard time adjusting to living in only a room as opposed to a house	Hardman, 2016
Hotel Stays	Health Impacts	Anxiety in children was increasing because they could not understand the reason of their current living situation	Hardman, 2016
Hotel Stays	Accessibility	Staying in hotels significant distances away from home created severe travel problems	Weiss, 2016
Hotel Stays	Accessibility	Issues arose with getting to work and	Hardman,

		getting children to school, but also smaller inconveniences such as traveling for laundry and for food	2016
Hotel Stays	Financial Cost	As of May 31, 2017, FEMA had paid approximately $42 million in hotel stays which averaged to $103 per night per room	Jones, 2017
Shelter at Home	Financial Cost	If a home could be made livable for under $15,000 with the state's approval, then FEMA would fund these temporary repairs leaving the homeowners to fund more permanent repairs	Crisp, 2017
Shelter at Home	Adaptability	Contrary to the thoughts of the governor, a Louisiana representative thought this program was a waste of tax dollars since the repairs being done were subpar and many homeowners were having to redo the repairs (using personal resources)	Committee on Oversight & Government Reform 2017
Shelter at Home	Adaptability	More oversight on the quality of the repairs was suggested in order to make this program more successful	Committee on Oversight & Government Reform 2017

Adaptability

The adaptability, A(j), of a temporary housing unit j is defined as the ability to transition into permanent housing without having to move into another unit. Here, adaptability is measured as a binary quality: the unit is either adaptable (1), or not (0), expressed as

$$A(j) = \begin{cases} 0 & not\ adaptable \\ 1 & adaptable \end{cases} \qquad \text{Eq. 1}$$

Customizability

The customizability, C(j), of a temporary housing unit j accounts for the number of features that a household can choose or change in order to fit their specific needs. Here, customizability is measured with three possibilities c_i: customizable interior or exterior appearance and decor, customizable layout or size of the temporary housing unit, and the ability to choose the geographic location of the temporary housing unit. Customizability is measured on a scale of 0 to 3 depending on how many customizable features the unit provides, expressed as

$$C(j) = \sum_{i=1}^{3}(c_i) \qquad \text{Eq. 2}$$

Local Economy Promotion

In this study, promoting the local economy, P(j), through temporary housing consists of two possible scenarios p_i: (1) does the location of the temporary housing allow for a circulation of funds within the disaster stricken community helping to build the economy back; and (2) does the temporary housing program create jobs for those who may be out of work post-disaster. P(j) is measured on a scale of 0 to 2 depending on how the temporary housing unit can stimulate the local economy, expressed as

$$P(j) = \sum_{i=1}^{2}(p_i) \qquad \text{Eq. 3}$$

Health Impacts
Health impacts, H (j), account for potential mental and physical health impacts caused by residing in a temporary housing type j. Mental health impacts could include depression, anxiety, sleep disorders, hyper-vigilance, suicide accounts and attempts, regressive behaviors, social withdrawal and isolation, memory loss, disorientation, and lack of concentration (Verderber, 2008). Physical health impacts could include domestic violence, headaches, nausea, vomiting, asthma diagnosis, and respiratory issues (Verderber, 2008). H(j) is measured as a binary variable: (1) if reports of health issues stimulated from residing in a particular type of temporary housing, and (0) if no health issues were documented, expressed as

$$H(j) = \begin{cases} 0 & \mathit{health\ issues} \\ 1 & \mathit{no\ health\ issues} \end{cases} \qquad \text{Eq. 4}$$

Environmental Impacts
Environmental impacts, E(j), are measured here as greenhouse gas emissions for each type of temporary housing j. To measure E, life cycle assessment (LCA) was performed using Athena EcoCalculator (ATHENA, 2017). The EcoCalculators for residential assemblies and commercial assemblies were used dependent on the type of temporary housing being evaluated (e.g., hotels were modeled as commercial assemblies).

Financial Cost
Financial cost, F(j), is estimated here as the dollar price required to fabricate, transport, and install the unit. See Table 1 for specific costs reported in the literature for the types of temporary housing being considered here.

Structural Integrity
Structural integrity, S(j), is defined here as the ability of the temporary housing unit to meet full service load and functionality requirements. HAZUS (DHS, 2015) damage states and building performance curves were adopted here for measuring the structural integrity of the temporary housing units. Damage states categorize physical damage into five levels (0 to 4), namely no damage, minor damage, moderate damage, severe damage, and complete damage, respectively. Values between 0 and 3 were assigned to each temporary housing j based on its damage state during occupancy, assuming that no one could still live in a damage state 4. In most cases, S(j) equals zero. When a household decides to shelter in place in their damaged residence instead of dislocating, S(j) exceeds zero, expressed as

$$S(j) = \begin{cases} 0 & \mathit{No\ Damage} \\ 1 & \mathit{Minor\ Damage} \\ 2 & \mathit{Moderate\ Damage} \\ 3 & \mathit{Severe\ Damage} \end{cases} \qquad \text{Eq. 5}$$

Hazard Vulnerability

Hazard vulnerability, V(j), is defined here as the ability of the temporary housing unit to withstand future disasters. HAZUS (DHS, 2015) damage states and fragility models for wind were adopted for V(j). The temporary housing type with the highest 50th percentile wind speed for a particular damage state was measured to have the lowest hazard vulnerability. Figure 3, which reproduces the damage-based wind fragility functions from HAZUS, was used to determine the 50th percentile wind speeds.

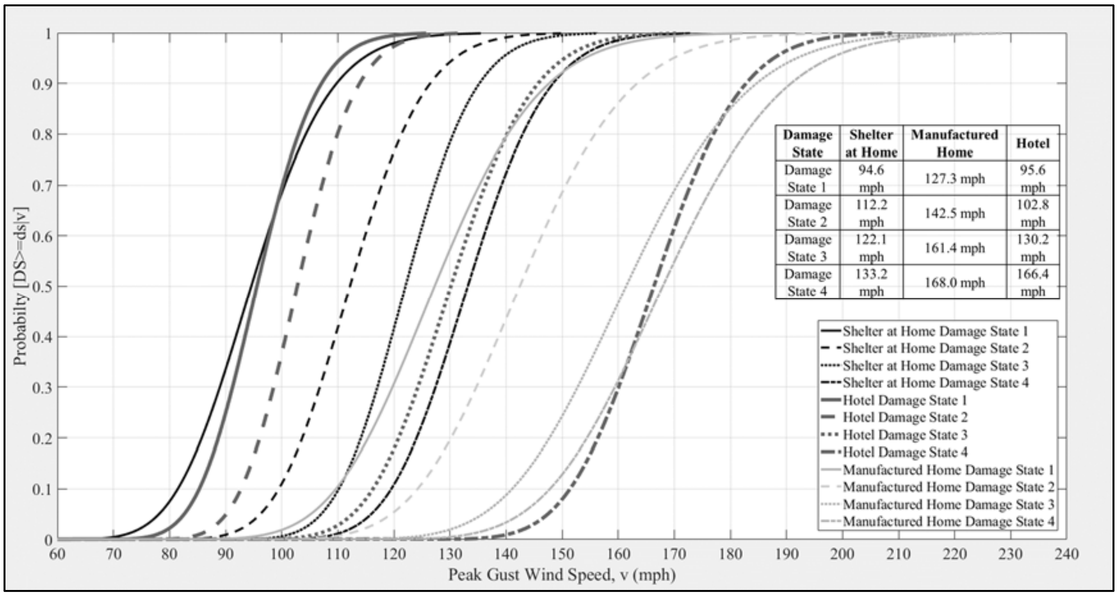

Figure 3. Damage State Fragility Functions (DHS, 2015)

The HAZUS 50th percentile wind speeds, w_i, for each temporary housing unit, j, were normalized with respect to the maximum 50th percentile wind speed for all temporary housing types at that specific damage state, i, expressed as

$$hv_i(j) = \frac{w_i(j)}{\max_j w_i(j)} \qquad \text{Eq. 6}$$

The normalized values are summed across damage states for each temporary housing j to determine the hazard vulnerability score, V(j), expressed as

$$HV(j) = \sum_{i=1}^{4} hv_i(j) \qquad \text{Eq. 7}$$

Quality of Life Index

The quality of life index, Q(j), measures the overall potential well-being of a household residing in a particular temporary housing unit. To formulate the quality of life index, the values of each quality for each type of temporary housing unit are summed. Depending on the pre- and post-disaster situation, households may value some qualities higher than others, thus weights are applied to each quality measure to account for household preference, expressed as

$$Q(j) = w_1 * A(j) + w_2 * C(j) + w_3 * P(j) + w_4 * H(j) + w_5 * E(j) + w_6 * F(j) + w_7 * S(j) + w_8 * V(j) \quad \text{Eq. 8}$$

The resulting Q(j) for each type of temporary housing is compared. The highest quality of life index provides the optimal temporary housing for that household.

EXEMPLIFYING TEMPORARY HOUSING FRAMEWORK

Four specific examples are presented to exemplify the framework provided in Figure 1. In each of the four examples, the disaster scenario was held constant: a hurricane disaster along the southeast coast of the United States. Two different household descriptions are examined, as described in Table 2. Weights are set for each quality measure based on observations from the literature, and for demonstrative purposes in evaluating the quality of life index. The third input, temporary housing options, is limited to four groups for brevity. Figure 4 depicts the units that are input to the temporary housing evaluation model, and how each expands into multiple layers of options.

Table 2: Household Descriptions

Household	Description
1	Minority race/ethnicity; low income; service employees, five to seven household members, with persons under 18 living in household; no insurance; old home (outdated code)
2	White non-Hispanic; middle class income; professional jobs, two adults in household without persons under 18 living in household; adequate insurance coverage

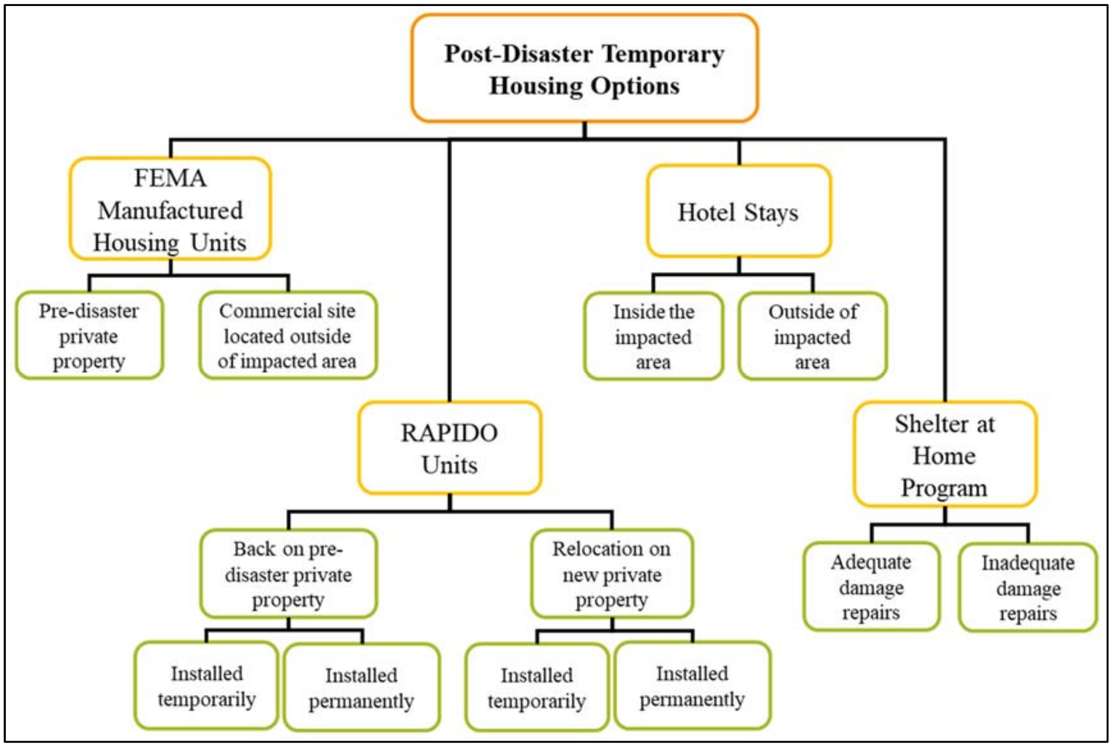

Figure 4. Post-Disaster Temporary Housing Options

Looking at Figure 4, two geographic locations were considered for FEMA manufactured units and hotel stays. These can affectively be described as accessible or inaccessible. A FEMA manufactured unit that is on the household's pre-disaster private property is accessible to the household's pre-disaster job, for example. A hotel that is within reasonable distance to their pre-disaster home is accessible to their pre-disaster jobs and schools, for example. FEMA manufactured units and hotels that are located far away, here described as outside of the impacted area, are considered inaccessible to the household's work, school, and other everyday needs. The temporary housing options in Figure 4 were evaluated using the methods described in the previous section to determine the optimal temporary housing solution for both households when considering accessible and inaccessible locations. Table 3 provides a summary of the eight qualities setting all weights equal to unity. Figure 5 provides Table 3 values in graphical form from both accessible and inaccessible locations, where the larger the area, the better overall performance and quality of life provided by the type of temporary housing. From Table 3 and Figure 5, FEMA manufactured units and hotels stays are observed to vary slightly depending on the location, while RAPIDO units and shelter at home programs are the same regardless of location.

Table 3. Temporary Housing Quality Values

Quality	FEMA Manufactured Units	RAPIDO Units	Shelter at Home	Hotel Stays
Accessible Location				
Adaptability	0.00	1.00	1.00	0.00
Customizability	0.00	3.00	2.00	0.00
Local Economy Promotion	1.00	2.00	2.00	1.00
Health Impacts	1.00	0.00	0.00	1.00
Environmental Impacts (kg CO_2eq)	16,000	15,000	67,000	10,000
Cost ($)	129,000	69,000	15,000	56,000
Structural Integrity (Damage State)	0.00	0.00	1.00	0.00
Hazard Vulnerability	0.77	1.00	1.00	0.82
Inaccessible Location				
Adaptability	0.00	1.00	1.00	0.00
Customizability	0.00	3.00	2.00	0.00
Local Economy Promotion	0.00	2.00	2.00	0.00
Health Impacts	2.00	0.00	0.00	2.00
Environmental Impacts (kg CO_2eq)	16,000	15,000	67,000	10,000
Cost ($)	149,000	69,000	15,000	56,000
Structural Integrity (Damage State)	0.00	0.00	1.00	0.00
Hazard Vulnerability	0.77	1.00	1.00	0.82

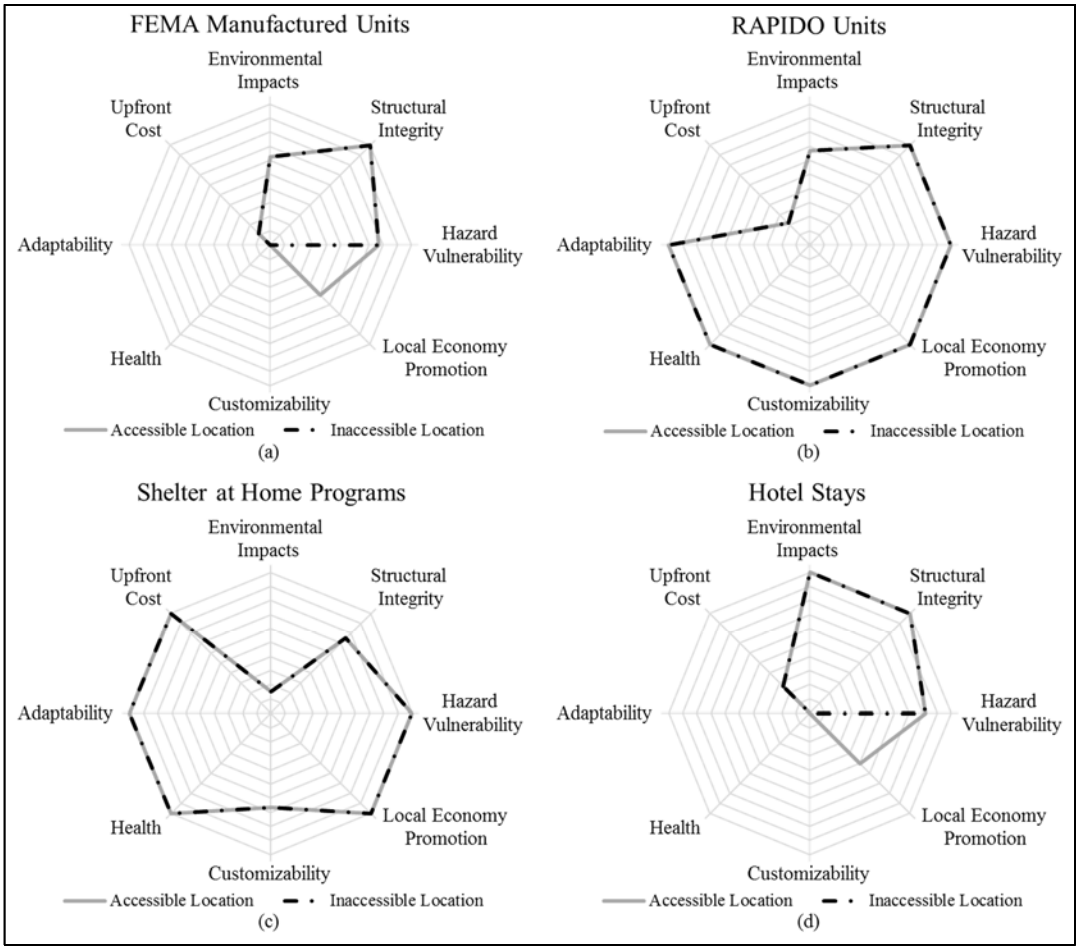

Figure 5. Temporary Housing Quality Values based on Location: (a) FEMA Manufactured Units (b) RAPIDO Units (c) Shelter at Home Program (d) Hotel Stays

The resulting quality tradeoffs provided in Table 3 and Figure 5 set the weights equal to unity. While this could be the case for a household, it is more likely that different households will have different preferences based on their specific needs. Household 1 (minority race/ethnicity, low income, service-employees, five to seven household members, with persons under 18 living in household, no insurance, old home) is considered first. Household 1 may have many priorities in a temporary home post-disaster, including a home that has high adaptability and customizability to accommodate the large family; a program that creates jobs as a way to earn income during recovery[1]; a home that has high structural integrity and hazard vulnerability to withstand any disasters to come since they may be residing in it for multiple years; and a unit that will promote (versus disrupt) the health of all occupants. Household 1 may be less concerned with environmental impacts and cost assuming the unit will be

[1] Previous disasters have shown people with service jobs are more likely to lose those jobs during a disaster leaving households that rely on their paycheck to lose their income (Masozera et al., 2007; Mueller et al, 2011; Van Zandt and Sloan, 2017).

supplied to them through an external funding program. Household 2 (White non-Hispanic, middle class income, professional jobs, two adults in household without persons under 18 living in household, adequate insurance coverage) may have different preferences with respect to a temporary home. This household has sufficient savings and repayment through their insurance. Structural integrity and hazard vulnerability may be of high importance to this household, along with ensuring their health and reducing the transition time to permanent housing so they can get back to their jobs and everyday life quicker. Table 4 provides the assumed weights assigned to Household 1 and Household 2.

Table 4. Quality Weights based on Household Preferences

Quality	Household 1	Household 2
w_1, Adaptability	1.00	1.00
w_2, Customizability	1.00	0.00
w_3, Local Economy Promotion	1.00	0.50
w_4, Health Impacts	1.00	1.00
w_5, Environmental Impacts	0.50	0.00
w_6, Financial Cost	0.50	1.00
w_7, Structural Integrity	1.00	1.00
w_8, Hazard Vulnerability	1.00	1.00

The weights provided in Table 4 are independent of location; they are applied to each quality regardless of whether the unit is accessible or inaccessible. Combining the values in Tables 3 and 4, into Eq. 8, the quality of life index is obtained. Figures 6 and 7 summarize the predicted Quality of Life index for each unit for both households in both accessible and inaccessible locations.

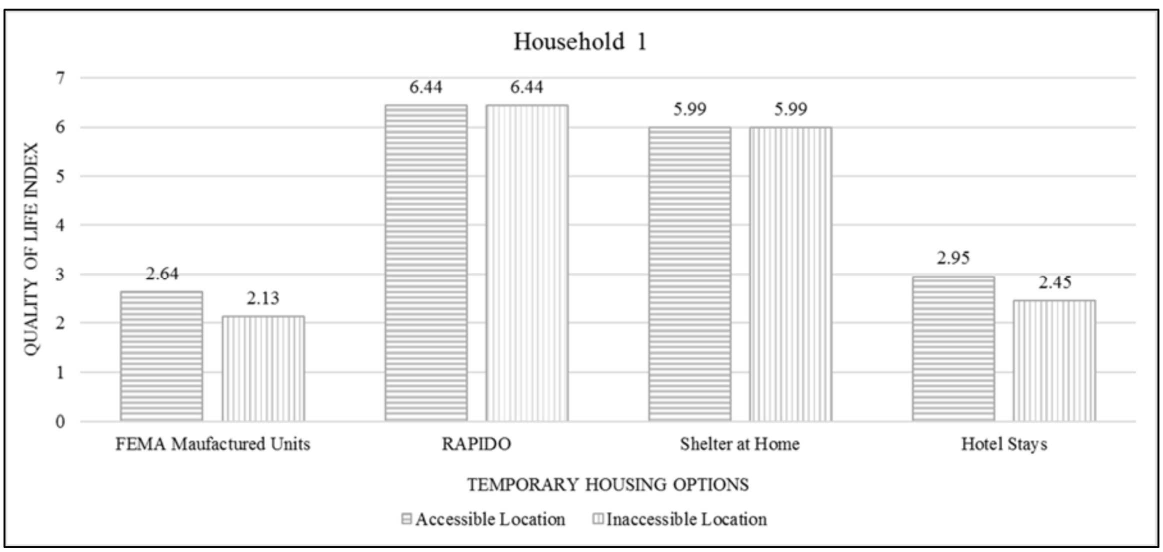

Figure 6. Quality of Life Index Comparison for Household 1

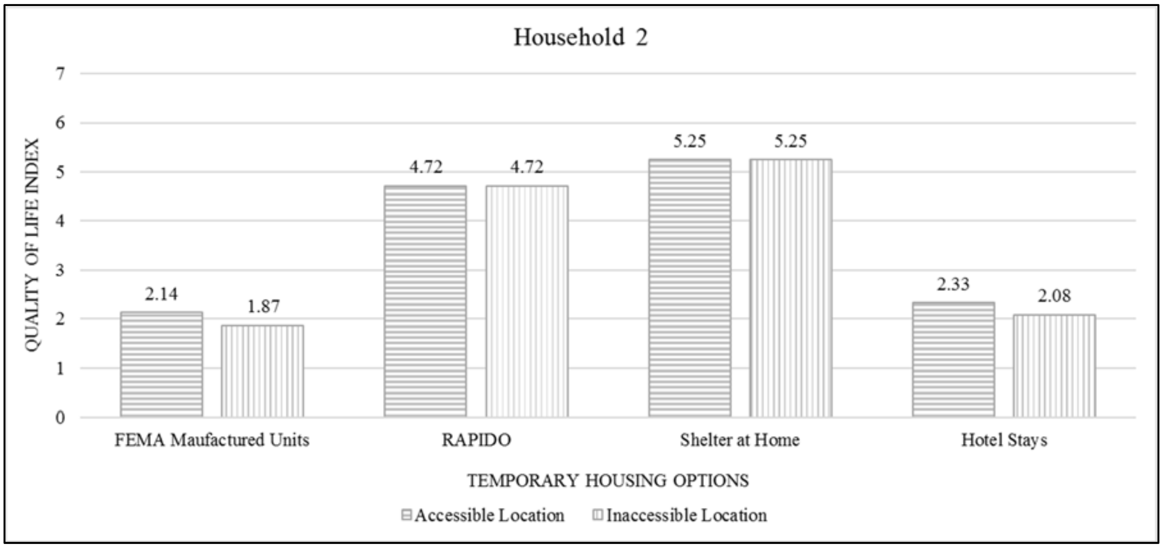

Figure 7. Quality of Life Index Comparison for Household 2

As shown in Figures 6 and 7, RAPIDO units provide the highest Quality of Life index for Household 1, and the shelter at home program provides the highest Quality of Life index for Household 2. A RAPIDO unit will ensure a customizable unit that will transform into a permanent home with high structural integrity, low hazard vulnerability, and simultaneously providing work to those who may have lost their jobs with the disaster providing a better overall recovery. Shelter at home program fits the needs of Household 2 by getting the household back into their home allowing for the return to their jobs as quickly as possible. Shelter at home program is the most cost-efficient solution for this household to receive the help they need.

SUMMARY AND CONCLUSION

This research is built on the fact that post-disaster temporary housing is more than just a roof over disaster victims' heads, and temporary housing has a greater meaning to households residing in them. Temporary housing is the transitional phase for households to gain somewhat of their normal pre-disaster lifestyle back. The more efficiently the temporary housing unit can provide this normalcy, the greater impact it will have on the household during recovery as exemplified through the quality of life index. The quality of life index includes temporary housing qualities associated with sustainability and resilience and is demonstrated with both common practices and innovative temporary housing solutions. It has been illustrated that each type of temporary housing unit, whether traditional or modern, has benefits in certain aspect over others. Custom built units, like the RAPIDO units, may seem like a positive solution for everyone, but when considering a particular household's needs, this may no longer be the case. No two temporary housing solutions perform in the exact same manner, and no two types produce the same exact quality of life index. Not only does the temporary housing unit contribute significantly to the quality of life index, but the type of household receiving the temporary housing unit affects it as well. In order to maximize the recovery process after a disaster, a household must be matched with a temporary housing unit that best fits their needs and produces the highest possible quality of life index for them.

For brevity, only four types of temporary housing units were considered here: FEMA manufactured units, RAPIDO units, shelter at home programs, and hotel stays. The framework can be extended to include other custom built units like Katrina Cottages, other rental options such as FEMA's Multi-Family Lease Rental Program and existing apartment buildings, other options for utilization of a pre-disaster home such as staying in the damaged home (this often occurs when no outside resources are available), and individual renovations performed solely by households. The framework can further be extended to include additional funding sources (e.g., government funded or personally funded). Additional sustainability and resilience qualities, such as the time taken to get households into a unit, cultural appropriateness of the unit, community involvement in the program, for example, can be added to the model, particularly after additional information is learned through future disaster experiences. The temporary housing types examined here were limited due to brevity, but the funding programs and quality measures were limited due to the amount of information found in the literature. As the number of disasters continue to grow year after year, information and literature will continue to expand and become available allowing for the ongoing growth and expansion of this particular research.

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Enhancing the Damage Prediction Capability of a Tornado Risk Assessment Tool

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ABSTRACT

Researchers have quantified the damage caused by tornadoes through post-tornado damage surveys in which damage is categorized by the EF-Scale. Those data are used in estimating the damaging wind speeds of the tornado. It is possible that the major tornado damage to residential communities can be estimated through a numerical analysis if the characteristics of the tornado strength and structural resistance of a community's buildings are known. This is the premise of a stochastic analysis tool developed at the University Florida that uses a limit state approach to estimate structural damage due to tornadoes and the associated economic losses to low-rise wood-framed structures. The Engineering-based Tornado Damage Assessment (ETDA) tool is written in MATLAB and includes four modules (a Tornado Wind Field Module, a Wind Load Module, a Wind-borne Debris Module and a Structural Resistance Module), to estimate the damage (defined as engineering damage ratios) for a group of houses within the tornado path. Version 1.0 of the ETDA tool uses a single prototype house to represent the heterogeneous distribution of houses found in a typical neighbourhood. The researchers hypothesize that the accuracy of the ETDA tool may be improved by adding more building prototypes to better represent the heterogeneous distribution of structures.

This research describes an approach for selecting additional prototype house models for use in the ETDA tool that can better represent the variety of typical houses impacted by a tornado. Through literature review and analysis of field data of tornado damaged houses, two additional prototypes are selected and the wind load characteristics are developed using Tokyo Polytechnic University's Wind Tunnel Database. The next step of this research is the development of the structural resistance module for the new prototype structures and then establish procedures to randomize the location and distributions of house prototypes within the existing dataset. Once the changes are complete, the version 2.0 ETDA tool will be used to conduct a sensitivity analysis to compare and evaluate the improvements in accuracy of damage ratio prediction (if any) by increasing the number of house prototypes from one to three.

INTRODUCTION

The United States experiences over 1200 major and minor annual tornado strike on average (Ashley 2007), resulting in about $982 million insured annual economic loss (Changnon 2009). However, with increasing population, the communities become more vulnerable to tornado damage with time (Ashley et al. 2014). Moreover, roughly ninety percent of the housing in the United States comprises of light wood-framed structures (Ellingwood et al. 2004). These structures are extremely vulnerable to damage because they lack the structural capacity to resist high wind loads generated in tornadoes (Standohar-Alfano et al. 2017).

Many towns in the United States have suffered from tornado damage, and in a few cases, post-tornado damage surveys have recorded those effects (Marshall 2002; Marshall et al. 2008; URS 2007). The patterns of tornado damage are related to both structural characteristics of the buildings and the intensity of the tornado-induced loads. Since 2011, post-tornado damage surveys have included geo-tagged photographs of damaged structures, providing researchers a means to calculate the distance away from tornado centerline. (Prevatt et al. 2011; Roueche and Prevatt 2013; Prevatt et al. 2016). By using the Rankine vortex model (Rankine and Miller 1888), it is possible to estimate the variation of wind speed with distance and therefore estimate the wind loads on structures.

Peng et al. (2016) developed a numerical tool for predicting tornado damage to residential structures. This probabilistic tool uses a Monte-Carlo simulation engine to determine the likelihood of failure for structures that are subjected to tornado wind loads. At present, the tool called the Engineering-based Tornado Damage Assessment (ETDA) tool has been evaluated by using its results to hindcast the damage caused by two previous tornadoes, namely 22nd May, 2011 Joplin, Missouri tornado (Peng et al. 2016) and the 26th December, 2015 Garland/Rowlett, Texas tornado (Prevatt et al. 2016). The results of ETDA tool estimated damage have been compared against actual post tornado observations.

In Version 1.0 of ETDA tool, the houses were modelled by a single prototype building model. This house is a single-story light-framed gable-roofed house with a gable roof sloping at 18^{o}. The prototype house model is 12.2 m long, 9.7 m wide and has an eave height of 2.4 m. The researchers hypothesize that the accuracy of the ETDA tool may be improved by adding more building prototypes to better represent the heterogeneous distribution of structures. However, adding additional prototypes would increase the complexity to the ETDA tool and the computational time for estimating damage. Thus, it is necessary to evaluate the effects of multiple house prototypes both on accuracy and the computational effort required to converge to a solution.

The objective of this paper is twofold: 1) to identify additional prototype houses for the ETDA tool which are typical to residential communities, 2) to calculate peak pressures on the roof of the ETDA tool's prototype houses for the wind load module of the ETDA tool.

The selected prototype houses must best represent typical structural characteristics of single family residential buildings. Initially, the typical house geometries and material characteristics are identified from the literature. In addition, the predominant roof shapes and building aspect ratios were determined from a dataset of house photographs taken following the 26th December 2015 Garland/Rowlett, TX tornado. It is assumed that this dataset is a reasonable representation of variability of house shapes and roofs. Typical building envelope materials and structural characteristics of houses are taken from Ellingwood (2004).

This paper describes the procedure for developing prototype houses for version 2.0 of the ETDA software. To determine the tornado-induced wind loads, the peak 3-second gust wind speed is obtained through methodology described in Peng (2015) and the appropriate wind pressure coefficients for building surfaces are obtained from Tokyo Polytechnic University's wind tunnel database (Tamura 2012). Ultimately the researchers selected two additional prototype houses for trial. Once the two additional prototype houses are fully implemented into the ETDA tool, the damage predictions of version 2 would be compared to version 1 and to the original empirical data on the damage observations.

BACKGROUND

Engineering-based Tornado Damage Assessment (ETDA) Tool

The Engineering-based Tornado Damage Assessment (ETDA) tool estimates structural damage and economic losses through numerical simulation of a translating tornado over a model building. The tool assesses the tornado effects on low-rise wood-framed structures (Prevatt et al. 2016) by integrating four modules within a Monte-Carlo simulation framework, specifically a) the tornado wind field module, b) the tornado wind load module, c) the wind-borne debris module, and d) the structural resistance module for a house during a tornado event. Figure 1 shows the framework of ETDA tool to estimate structural damage for eight building components, namely roof cover, roof sheathing, roof-to-wall connections, wall cover, wall sheathing, windows, entry doors and the garage door. Economic loss to houses is calculated using the empirical relationship between structural damage and economic loss from Bhusar (2017).

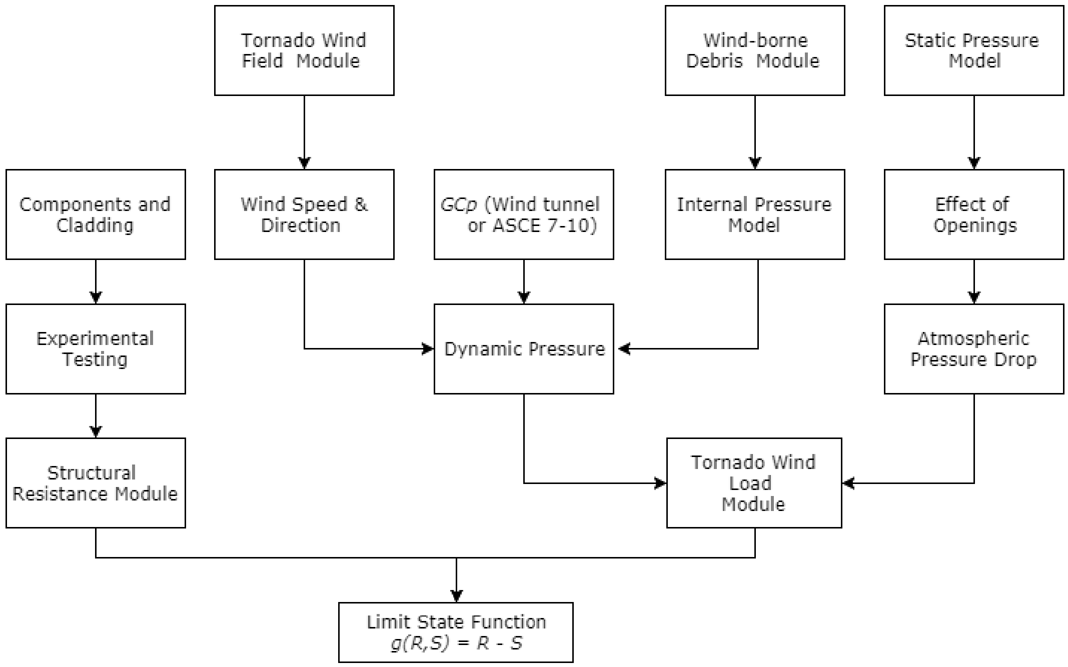


Figure 1 Framework of ETDA tool for estimating damage for each component of house (Peng et al. 2016)

The Engineering-based Tornado Damage Assessment (ETDA) tool is calibrated using the houses damaged in the 26 December 2015 Garland/Rowlett Texas tornado. Prevatt and Roueche (2015) conducted a post-tornado damage investigation and documented damage to 718 houses using geo-tagged photographs. For each house, at least four photographs covering all the four sides of the house were taken to ensure the complete documentation of damage. Using the photographs of damaged houses, damage ratio to eight house component is assigned. The damage ratio is defined as the ratio of the quantity or area of a given house component that was damaged to the total quantity or area of the house component. Based on the geotagged location of houses, the distance of houses to tornado centerline is estimated and using the estimated path of the tornado, the orientation of houses is estimated. The distance and orientation of houses with respect to tornado path are used as input parameters in the ETDA tool to define house model characteristics. To simulate numerical model of a tornado, maximum tangential wind speed, radius of tornado and translational velocity are also used as input. Using the house information and tornado information, damage to houses is estimated for the eight house components mentioned previously.

Performance of existing ETDA Tool

The ETDA tool was used to estimate structural damage for the houses damaged in 26th December 2015 Garland/Rowlett tornado. Figure 2 shows the results of observed damage and ETDA tool estimated damage for the Garland/Rowlett tornado.

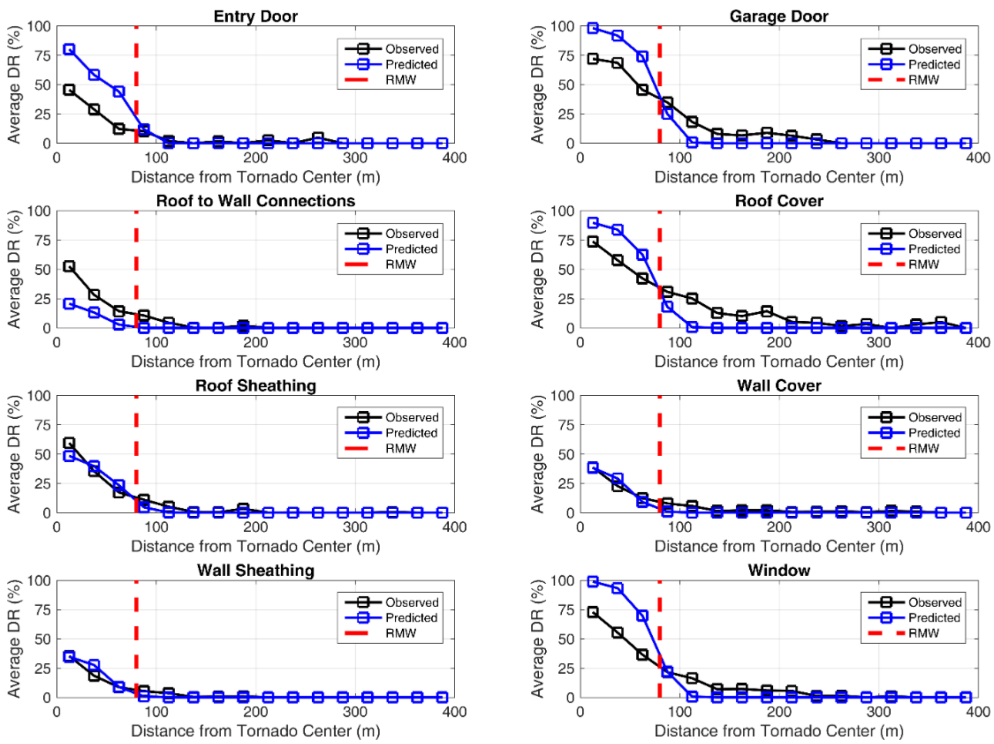


Figure 2 Average observed and ETDA tool predicted damage ratios (DR) for the Garland/Rowlett tornado. Bin size is 25 m. The red dashed line indicates the radius to maximum wind speeds (Bhusar 2017).

The ETDA tool shows a good damage prediction capability, however, the comparison of ETDA tool estimated damage and field observed damage shows a mixed trend of over-prediction and under-prediction. We hypothesize that this trend of damage prediction can be attributed to three factors: 1) the house geometry of the field house is different than ETDA tool's prototype house, 2) the construction practices and the structural capacities of field house is different than ETDA tool's prototype house, 3) the assumed tornado track and/or intensity is in error, causing the tornado loads on the field house to be different than on ETDA tool's prototype house. The present work focuses on the first factor, i.e. improving the ETDA tool by incorporating a variety of houses found typically in a residential community.

METHODOLOGY FOR IMPROVING PERFORMANCE OF ETDA TOOL

To improve the predictive capability and applicability of the ETDA tool, typical houses of the United States should be incorporated while evaluating damage to communities. Two typical houses which can represent the diversity of typical houses are selected as additional prototype houses for the ETDA tool. Peak pressures on the roof sheathing of ETDA tool's three prototype houses are evaluated to demonstrate the variation in magnitude and distribution of pressures. Peak pressure on roof sheathing is evaluated because roof sheathing failure is frequently observed by post tornado damage surveys (Roueche and Prevatt 2013) and can lead to structural collapse or damaging water ingress.

Step 1: Identification of typical house configurations of the United States
Prevatt and Roueche (2015) through their ground survey of the 26th December 2015 Garland/Rowlett Texas tornado obtained geo-tagged photographs of 718 houses. Based on visual inspection of photographs and the local county tax appraiser database, building characteristics such as roof shape, number of stories are determined. To calculate floor area for each house the plan view of houses is used. The plan view is obtained from Google Maps and the measure tool is used to trace the perimeter of the house, based on which the floor area of the house is calculated.

Presently, due to time constraints, roof slope for a small sample of 19 houses is determined. The houses are selected randomly from the total of the surveyed houses. The roof slope is estimated by using the front elevation photograph of the house for hipped roof houses and by using the side elevation of the house for gable roof houses. The front elevation and side elevation of houses are obtained from Google Maps Street View. The photograph of front elevation and side elevation is pasted in AutoCAD and a triangle is superimposed over the sloped roof. The lengths and the angles of the triangle can provide a fair idea of the roof slope. Based on roof slope of 19 houses, 58% of houses have roof slope greater than 27^0, while 42% of houses have roof slope less than 27^0.

The aspect ratio (length to width ratio) of the same 19 damaged houses is calculated by using the plan view of the house. The plan view is obtained from Google Maps and the measure tool is used to obtain the ratio of the floor dimensions. The aspect ratio is varying from 1.0 to 1.5 for 94% of houses, while the aspect ratio is 2.1 for 6% of houses.

Thus, a database of house information is developed for the 718 surveyed houses. It is observed that 60% of houses have a hipped roof and 40% have a gable roof, while 68% of houses are single storied and 32% are two storied. The format of house information using 5 houses is shown in Table 1.

Table 1 Format of house information showcasing 5 houses from the 718 houses damaged in 26th December, 2015 Garland/Rowlett, TX tornado

House Number	Distance (m)	Roof type	Roof slope	No. of stories	Aspect ratio (length/width)	Floor Area (m^2)
1	144.73	Hip	20^0	1	1.0	166.20
2	127.41	Gable	45^0	1	1.25	141.58
3	100.69	Hip	16^0	1	1.0	166.20
4	0.47	Gable	33^0	1	1.43	188.87
5	87.58	Hip	31^0	2	1.43	254.93

Step 2: Selection of prototype houses for the ETDA Tool
Table 2 summarizes the building characteristics of typical houses based on the post-tornado damage survey conducted by Prevatt and Roueche (2015).

Table 2 Building characteristics identified for a typical house of the United States

Building Property	Typical house characteristic
Roof shape	Gable and hipped roof
Length to width ratio	1.0 to 1.5
Number of stories	1, 2
Roof slope	18^0 to 45^0

The current (first) prototype house is a gable roof sloping at 18^0, having a 1.25 aspect ratio and 2.4 m height to the eave. To cover the observed range of construction, the second and third prototypes selected have aspect ratios of 1.5 and 1.0 respectively. Further, since 32% of the houses in the Garland/Rowlett dataset were two-storied, a two-storied house is selected as the third prototype with a 4.8 m height to the eave. The roof slopes selected for the second and third prototypes are 45^0 and 27^0 to cover the range of roof slopes identified in Garland/Rowlett dataset, Gavanski et al. (2013) and ASCE 7 (2010). Table 3 shows the classification of gable and hipped roofs according to roof slope. Table 4 shows the three ETDA tool prototypes and Figure 3 shows the photographs of damaged houses similar to the additional prototypes found in Garland/Rowlett.

Table 3 Roof slopes used for gable and hipped roofs in Gavanski et al. (2013) and ASCE 7 (2010)

Roof slopes	Gavanski et al. (2013)		ASCE 7 (2010)	
	Gable	Hipped	Gable	Hipped
7^0	-	-	✓	✓
18^0	✓	✓	-	-
27^0	✓	✓	✓	✓
45^0	✓	✓	✓	-

Table 4 Prototype houses for the ETDA tool

Prototype No.	Roof type	Roof slope	Aspect ratio	Number of stories
I[a]	Gable	18.4°	1.25	1
II[b]	Hipped	45°	1.5	1
III[b]	Gable	27°	1.0	2

a Current ETDA tool prototype house

b Proposed ETDA tool prototype house

(a)

(b)

Figure 3 Photograph of damage to houses similar to the additional prototype houses from the 26th December 2015 Garland/Rowlett, TX tornado. (a) Prototype II (b) Prototype III

Step 3: Determination of enveloped peak wind pressure coefficients on the roof
To estimate the wind loads on the roofs of the ETDA tool's prototypes, peak pressure coefficients on the roof-sheathing panels are calculated. The sheathing panel size used is 1.2m x 2.4m (4ft x 8ft) which is typical of North American wood-frame construction (Gavanski et al. 2013). Two wind tunnel databases were reviewed for calculation of peak pressures on the roof. The first database, called the University of Western Ontario (UWO) database consists of 37 low-rise gable roof configurations. The second database, called the Tokyo Polytechnic University (TPU) database consists of 116 low-rise building configurations with gable, hipped and flat roof shapes. The TPU database covers more diverse building configurations which are typical to residential communities, and hence is selected for calculating the peak pressures on the roof of the prototype houses.

Tamura (2012) summarizes the experimental setup and data archival method used to store the results from the TPU wind tunnel study. The wind tunnel data is publically available on their website for 0^0 to 90^0 wind angles with 15^0 increment. Table 5 shows the building properties of all the test configurations in full scale dimensions from TPU database. Figure 4 shows the 32 house configurations of the gable roof with one floor area, while Figure 5 shows the hipped and flat roof house configuration from the TPU database.

Table 5 Complete model set of the Tokyo Polytechnic University database (Tamura 2012)

Roof Type	Length (m)	Width (m)	Aspect ratio	Eave height (m)	Roof-slope β (^{0})	Number of building models
Flat	16, 24, 40	16	1.0, 1.5, 2.5	4, 8, 12, 16	0	12
Gable	16	16	1.0	4, 8, 12, 16	4.8, 9.4, 14, 18.4, 21.8, 26.7, 30, 45	32
Gable	24	16	1.5	4, 8, 12, 16	4.8, 9.4, 14, 18.4, 21.8, 26.7, 30, 45	32
Gable	40	16	2.5	4, 8, 12, 16	4.8, 9.4, 14, 18.4, 21.8, 26.7, 30, 45	32
Hipped	24	16	1.5	4, 8, 12, 16	26.7, 45	8

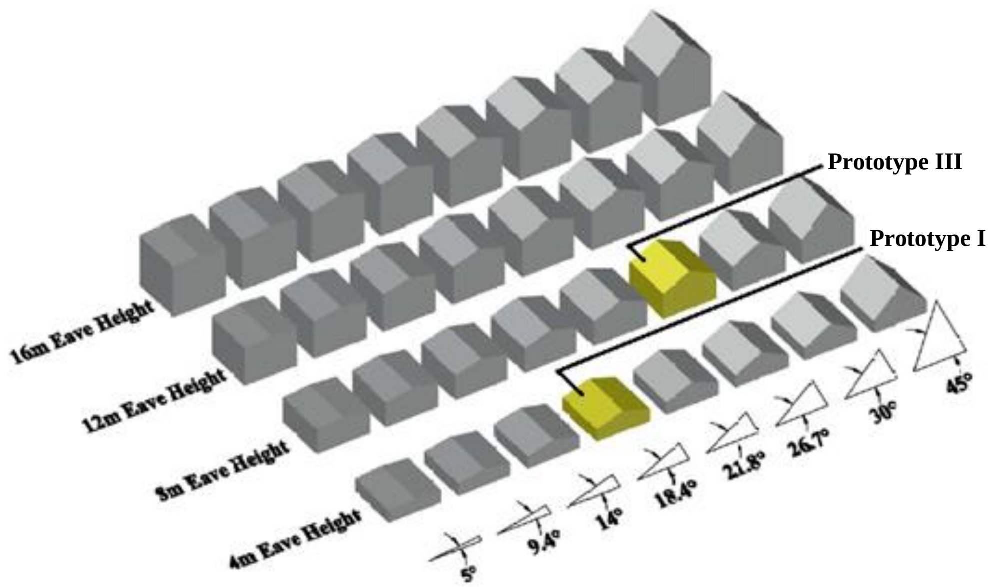
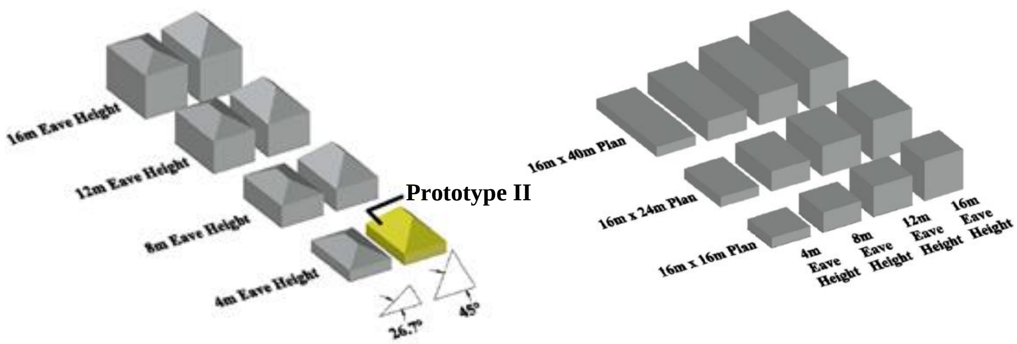


Figure 4 Gable roof house configurations used in the Tokyo Polytechnic University dataset



(a) **(b)**

Figure 5 (a) Hip roof and (b) flat roof house configurations used in the Tokyo Polytechnic University dataset

To calculate peak wind pressure coefficients on the roof sheathing of the three prototype houses, an array of 1.2m x 2.4m sheathing panels is projected on the roof surface. The pressure taps for the selected TPU configuration are overlaid on top of the sheathing panels. Figure 6 shows the pressure tap and sheathing panel arrangement for Prototype II house configuration, while Figure 7 shows the same for Prototype III.

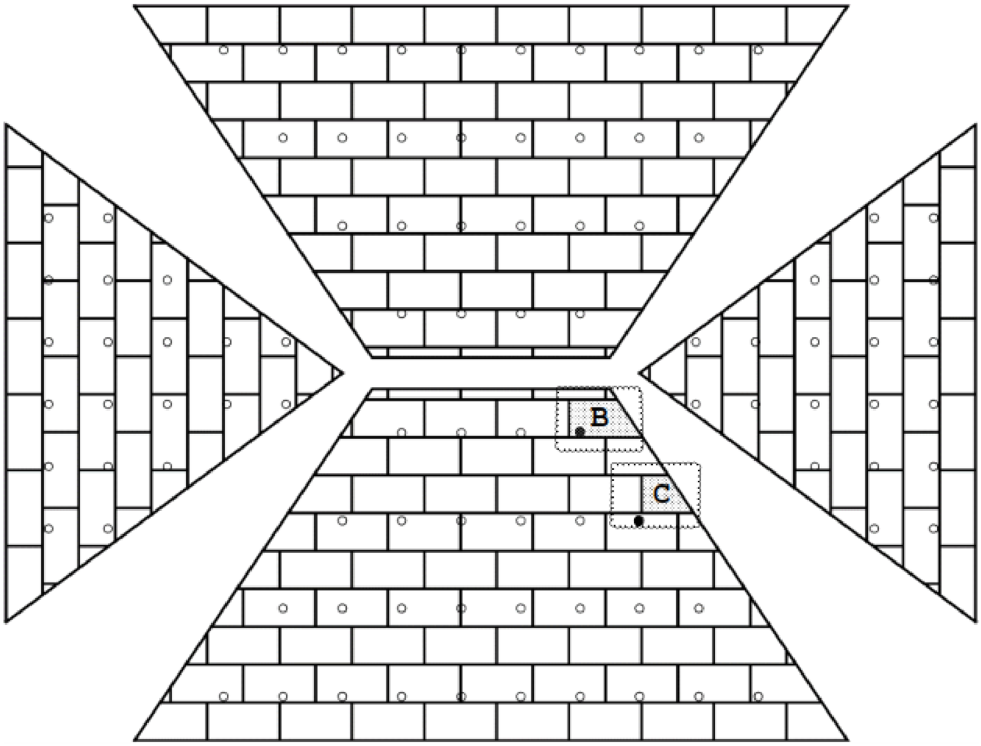


Figure 6 Prototype II roof plan with pressure taps overlaid on sheathing panels

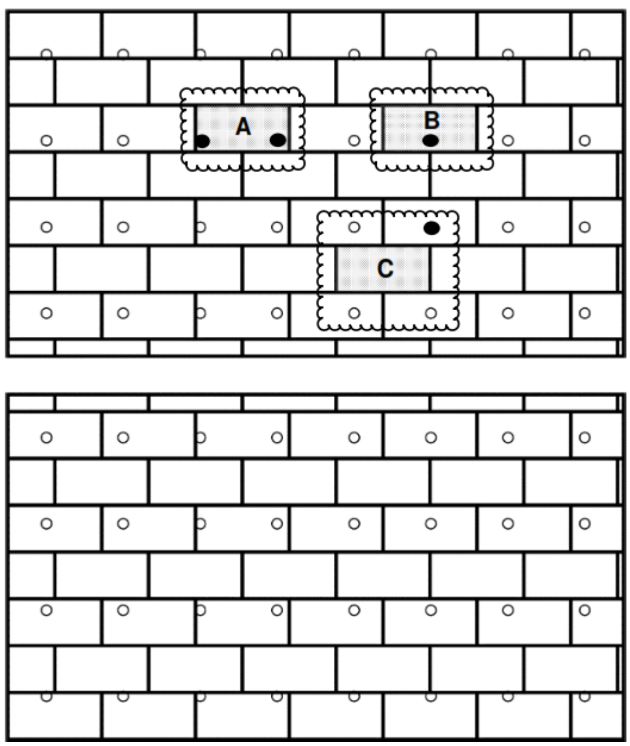


Figure 7 Prototype III roof plan with pressure taps overlaid on sheathing panels

A preliminary approach is used to calculate peak wind pressure coefficients for each sheathing panel. Three cases for the arrangement of pressure taps over the roof are used. The three cases are illustrated in Figure 8.

Case A: When two pressure taps are inside the sheathing panel boundary; the arithmetic average of the two pressure time history is used.

Case B: When one pressure tap is inside the sheathing panel boundary, the single pressure tap time history is used.

Case C: When no pressure tap is inside the sheathing panel boundary, the pressure tap time history of the nearest pressure tap from the centroid of the sheathing panel is used.

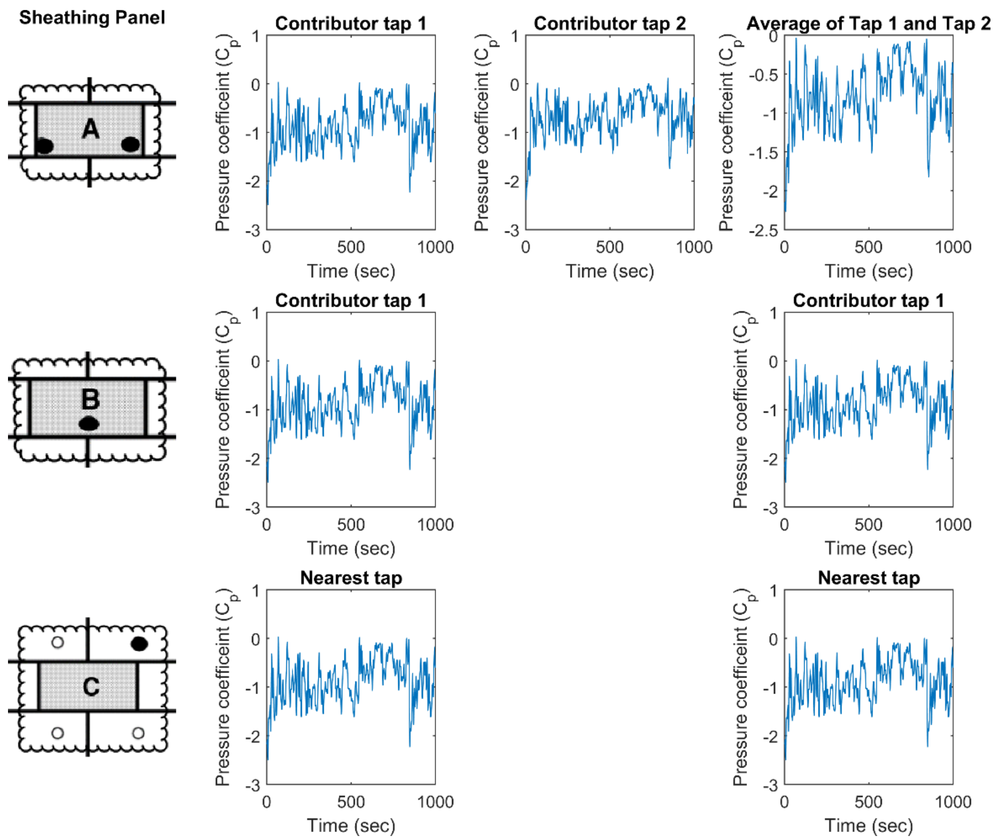


Figure 8 Cases used for determining wind pressure time history for the sheathing panels

The pressure time histories for each sheathing panel is divided into 10 equal segments corresponding to peak evaluation time of 1-minute. Minimum peak pressure coefficient for each sheathing panel is estimated by using Lieblein BLUE formulation (Lieblein 1976). The 78th percentile peak value is selected as the peak pressure coefficient for all the sheathing panels. The results of TPU wind pressure coefficients are re-referenced to mean approach velocity at mean roof height in suburban terrain. In the current study, the results of peak pressure coefficients from TPU database are normalized to 3-sec gust wind speed at 10m height in open country terrain using the conversion method from St Pierre (2005). The same procedure is repeated for all the wind angles $\theta = 0° \ to \ 90°$. Minimum peak value is determined from all the wind angles to obtain enveloped peak value. Figure 9 shows the peak pressure coefficients on the roof for the seven wind angles and the enveloped value for Prototype III.

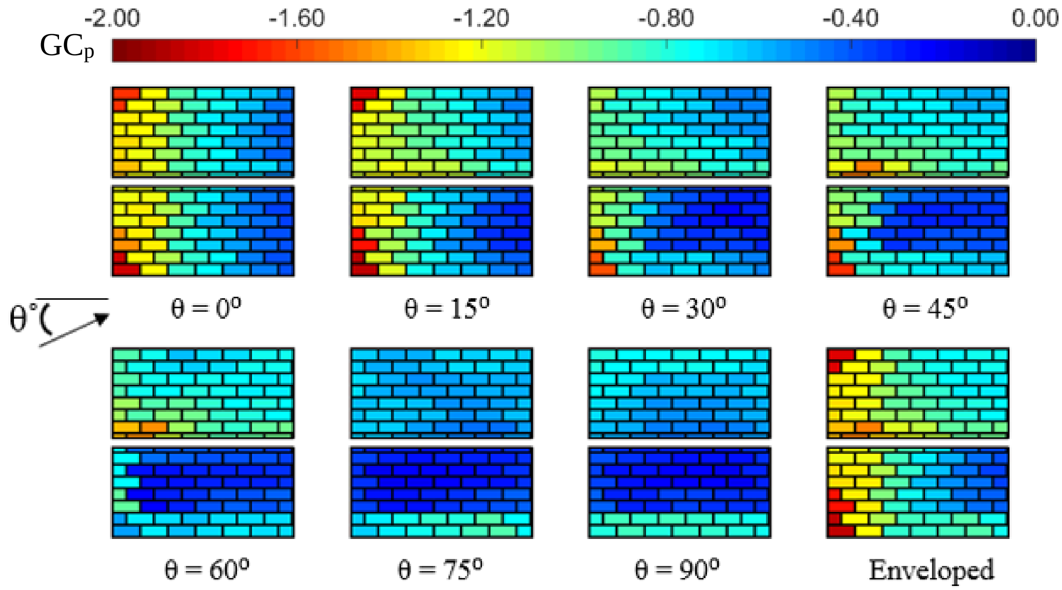


Figure 9 Peak wind pressure coefficients for Prototype III enveloped between 0 and 90°

Figure 10 shows the enveloped peak pressure on the roof of Prototype I of the ETDA tool, while Figure 11, Figure 12 show the same for the two additional prototypes.

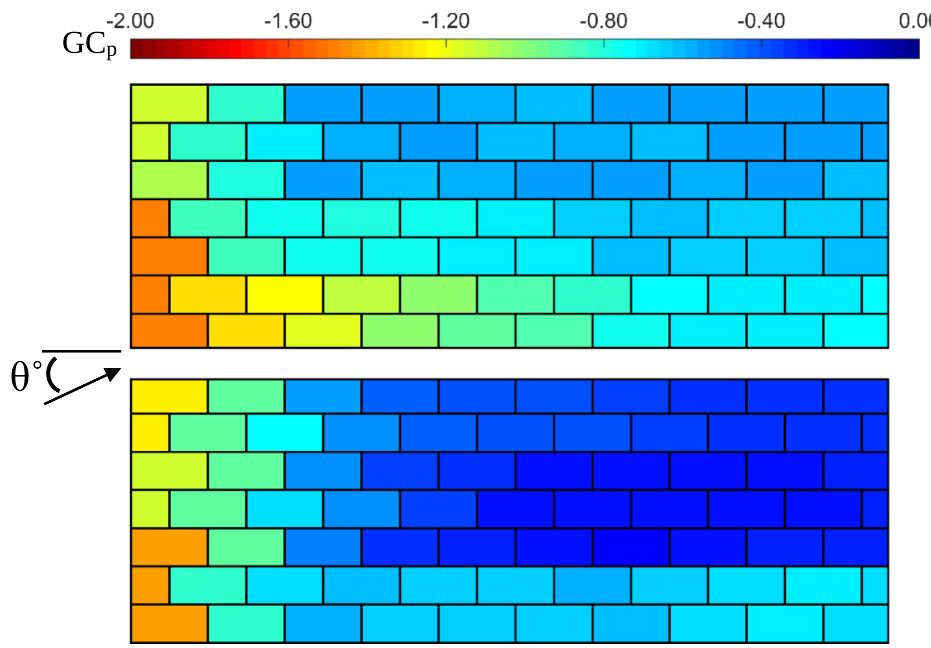


Figure 10 Peak wind pressure coefficients for Prototype I enveloped between 0° and 90°

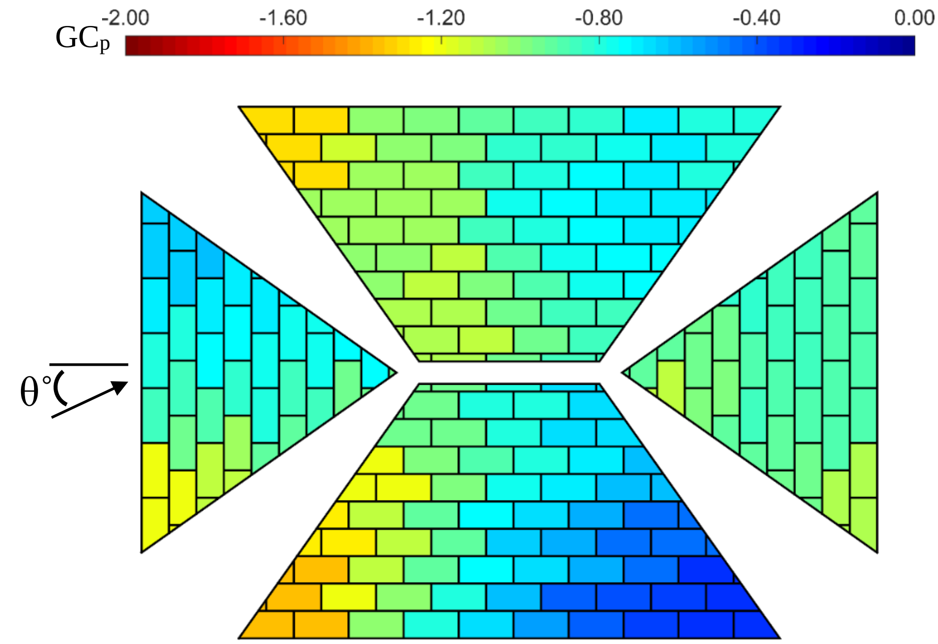


Figure 11 Peak wind pressure coefficients for Prototype II enveloped between 0° and 90°

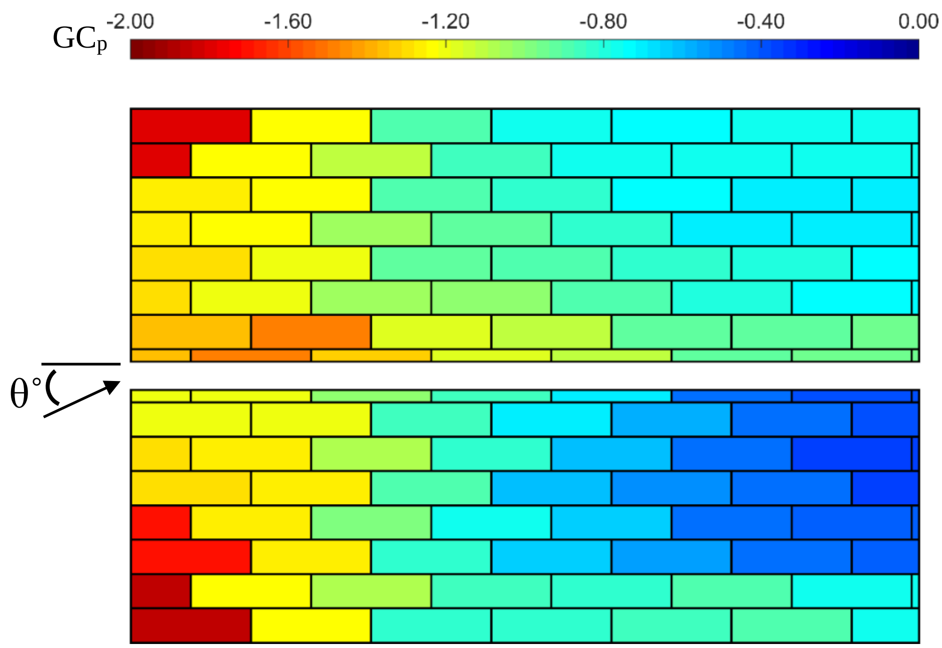


Figure 12 Peak wind pressure coefficients for Prototype III enveloped between 0° and 90°

It can be observed from the Figure 10, Figure 11, and Figure 12 that pressure on the roof for Prototype III, which is two storied is higher in magnitude than both Prototype I and II, which are single storied. For all the three prototypes, the pressures are highest along the windward roof corner, while it is comparatively lower everywhere else. The hipped roof (Prototype II) has intense pressures along the windward hip lines, while the intense pressures on the gable roof models (Prototype I and III) are along the windward roof edge. Between Prototypes I and II, there are more highly loaded panels on Prototype II, indicating the effect of increased roof slope. The magnitude and distribution of pressures are different between the three prototypes. The additional prototype house models should be able to better reflect the heterogeneous distribution of houses present in the communities.

CONCLUSIONS

Through a literature search and using post-tornado damage survey of the 26th December 2015 Garland/Rowlett TX tornado the typical configurations for single-family residential houses were identified. This paper described the procedure used to select two additional prototype house shapes for use in the Engineering-based Tornado Damage Assessment (ETDA) Tool. The wind pressure distributions are influenced strongly by the plan aspect ratio of structures and so the prototypes cover a range of aspect ratios from 1.0, 1.25 and 1.5. Wind tunnel results from the extensive wind tunnel dataset from the Tokyo Polytechnic University's Wind Tunnel are used to determine external wind pressure coefficients on the roof of prototype houses. The most common roof shapes are the gable roof and hipped roof structures, and so for sensitivity analysis component of this project, Version 2.0 of the ETDA Tool will include two gable roofed prototypes; a) single-story house, 18.4^0 roof slope having a 1.25 aspect ratio, and b) two-story house, 27^0 roof slope, having a 1.0 aspect ratio. A hipped roof structure is selected as the third prototype, having a 45^0 roof slope and aspect ratio of 1.5.

The ETDA tool with three prototype house models should be able to better reflect the houses typically present in the United States. Future work will integrate the selected additional prototypes to the ETDA tool and assess its performance against the previous version of the ETDA tool and with original empirical data from damage observations.

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Closing the Post-Occupancy Performance Gap in Zero Energy Housing

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ABSTRACT

Buildings continue to have a large impact on the environment consuming 40% of U.S. energy and 70% of U.S. electricity in 2015. Buildings are complex systems, yet architecture, engineering, and construction (AEC) professionals often perform their work lacking a formal post-occupancy feedback process that informs the efficacy of zero energy performance goals when using energy simulations during design. This gap in simulated versus measured outcomes creates uncertainty in the housing industry and impedes the market transformation toward zero energy housing. The aim of this paper is to contribute to closing the post-occupancy performance gap in zero energy housing. Utilizing a descriptive and exploratory case study, researchers evaluate longitudinal evidence of 8 all-electric zero energy housing units located in the mixed-humid climate to evaluate 1) originally simulated versus measured energy performance of a senior, affordable zero energy development; 2) the impact of actual weather versus simulated standard climate on year to year energy; and 3) alternative simulation tools that could allow to better capture potential occupant impacts in zero energy housing. Preliminary findings suggest human factors have a large impact on achieving actual zero energy performance goals and energy simulation tools utilized during design may not capture the volatility of these impacts accordingly. Historically, residential buildings have been enclosure and environmental system dominated in the context of energy consumption. Aggressive, top-down enclosure and system requirements through building energy codes and federal efficiency mandates are quickly shifting loads in residential buildings away from these traditional loads toward water heating and miscellaneous electric loads (MELS). A socio-technical

system (STS) model is proposed to close the post-occupancy gap and improve the operational effectiveness of zero energy housing.

INTRODUCTION

Over the last 25 years, the distributions of U.S. residential building end-uses have shifted from space heating dominated toward water heating and MELs, reflecting improvements of performance in building enclosure systems due to stricter energy codes. Since 2009, the cost of residential solar photovoltaic systems (solar PV) has fallen more than 60% (Ran et al., 2015). The race towards zero energy housing is well underway and will continue to push space heating loads and end uses away from the spotlight. This shift in performance creates an opportunity to improve human-building system relationships.

The residential AEC industry currently lacks verified performance standards and real-time data feedback once a certificate of occupancy is issued. We rely on static monthly utility bills that lag and mask occupant behavior, lawsuits and anecdotal business development trends as our feedback mechanisms for the design of a complex, system-based product, mostly ignoring occupant behavior and interaction with these systems. A better understanding of predicted vs. measured energy performance of buildings could develop and/or refine tools allowing professionals throughout the supply chain to more accurately model energy consumption for the built environment. As a result, the aim of this work is to: 1) increase model accuracy for high performance housing (HPH) in terms of occupancy context and 2) suggest a human factor based socio-technical model to close the post-occupancy gap in HPH. Tools that accurately and precisely predict the performance of buildings and/or buildings systems for different usage/occupancy patterns would reduce the information gap that currently inhibits our ability to understand and confidently communicate the return on investment for zero energy buildings.

BACKGROUND

This study reports findings from an affordable, rental housing development that provides housing for seniors (55+ years old). The project was developed and is currently managed by a non-profit organization in Virginia, USA. The case study property (termed CS-ZE, hereafter) is a measured zero energy development located in Blacksburg, VA (Climate Zone 4A) consisting of four single-story, senior duplexes. CS-ZE units are all electric and individually sub-metered, yet residents are not responsible for their utility bills (owner paid). Further, the project pursued third party certification programs (EarthCraft House and Energy Star) that assisted the project team with setting performance goals, energy modeling during design, and verification and diagnostic testing (enclosure tightness and duct tightness) during construction. CS-ZE occupancy and data collection began in fall 2014. An overview of the development, building system, and enclosure characteristics can be found in Table 1.

Table 1. Development, building system and enclosure characteristics

CS-ZE Sample Apartments		
Development Context	**Enclosure** (unit-level)	**Systems & MELs** (unit-level)
▪ Location: Blacksburg, VA, USA ▪ Climate zone: 4A, mixed-humid ▪ Population: Senior, affordable ▪ Heating Degree Days (HDD): 5446 ▪ # of Units: 8 ▪ # of unit types: 2 ▪ # of buildings: 4 ▪ Fuel source(s): Electric, net-metered solar photovoltaic (PV)	▪ Condition area/apt: 966 ft^2 (90 m^2) ▪ Volume/apt: 7728 cf (218.8 m^3) ▪ Window to wall ratio: 0.141 ▪ Window u-value: 0.25 BTUh/ft^2/°F ▪ Window SHGC: 0.27 ▪ Slab u-value: 0.05 BTU/hr/ft^2/°F ▪ Wall u-value: 0.04 BTUh/ft^2/°F ▪ Ceiling u-value: 0.02 BTUh/ft^2/°F ▪ Avg. enclosure tightness: 2.0 ACH_{50}	▪ Space heating: 9K Btu/h, 18 SEER ▪ Space cooling: 9K Btu/h, 10 HSPF ▪ Ducted air system tightness: 1% ▪ Water heating: 2.75 EF, 50 gal. electric hybrid ▪ Ventilation: balanced,1 CFM/Watt exhaust fan with passive inlets ▪ PV system: south-facing, 3.8 kWp ▪ Lighting: 100% LED ▪ Dishwasher, clothes washer, dryer: Energy Star rated

Zero Energy Housing

Zero energy buildings are generally defined as buildings that generate as much energy as they consume on site on an annual basis (Torcellini et al. 2006; Crawley et al. 2009; Ueno, & Straube 2011; Reichard et al. 2016). Reporting on 19 net-zero energy homes in New England, Thomas and Duffy (2015) developed a basic overview of the technologies commonly found in this type of HPH: optimized building enclosure systems, efficient lights and appliances, right sized heating, ventilation, and air condition systems (HVAC), optimized domestic water heating systems, and on-site generation; typically, a solar photovoltaic (PV) system. Certified professionals established net-zero performance goals for CS-ZE during the conceptual design phase.

Climate and Weather

Climate impacts building performance. AEC professionals must consider the climate context where they are working in order to manage building performance-related risk. The existing literature representing measured zero energy and near-zero residential buildings is dominated by single-family detached housing located in cold, mixed-humid and hot-humid climates; (Bergey and Ueno, 2011; Thomas and Duffy, 2013; Parker, 2009; (Norton, P., Hancock, E., Barker, G., & Reeves, P., 2005). Unlike previous work, this study reports energy use data for a zero energy multifamily project located in Climate Zone 4A, a mixed humid climate. According to the EIA (2016), 31% of the U.S. housing stock is located in a mixed-humid climate.

Conversely, *weather* refers to atmospheric conditions (ambient temperature, relative humidity and solar radiation) observed in a geographic area that vary year to year.

Literature suggests *weather* impacts residential energy use and represents an important variable when performing post-occupancy energy use analysis (Bros-Williamson et al., 2016; Touchie et al. 2013). Ambient air temperature, relative humidity, and solar radiation drive space conditioning to maintain occupant thermal comfort, therefore weather-normalized energy use data enables a comparison of building performance by isolating the influence of year to year weather variability (Sailor & Vasireddy 2006). Preliminary work by the authors suggests that HPH located in the mixed-humid climate zone 4A, have enclosure loads that are reduced and weather variability becomes less important, driving our need to better understand and ultimately reduce the energy penalty caused by variability in occupant behavior (Zhao et al. 2017).

Occupants in Socio-technical Systems

Literature suggests occupant behaviors considerably affect residential energy use (Santin, Itard & Visscher, 2009; Yu, Fung, Haghighat, Yoshino, & Morofsky, 2011; Kavousian, Rajagopal & Fischer, 2013). Parker (2003) noted that the length of showers and the frequency of showers were correlated with cooler weather; therefore, domestic water heating increasingly contributed to energy consumption loads in the sample. The use of appliances such as dishwashers, clothes washers, and dryers has been discussed in literature related to resident behavior as well (Fischer 2008; Hoak, Parker & Hermelink 2008; Ek & Söderholm 2010). Moreover, it has been noted that educating occupants on energy efficiency may be the next frontier for high-performance buildings (Brandemuehl & Field 2011). The literature suggests occupant behavior impacts building performance, yet few studies evaluate the relationship between occupants and HPH. Zhao et al. (2017) measured and then isolated the interaction effects of technology and occupant behavior in 300 HPH multifamily units. The study finds that technologies account for 42% of energy use in HPH, while 50% of the energy use is correlated to human factors.

Zero energy housing relies on an integrated systems approach (extending to technology and human interaction), yet the existing literature describes occupant behavior as a discrete variable; Isolating the human from the human-system relationship is in conflict with the systems view. The authors identify the lack of models and/or frameworks that acknowledge, assess, and design for the human-building relationship. To fill this gap, the authors propose a socio-technical system (STS). The STS theory was empirically developed in the late 1940s and 1950s by Emery and Trist, and then further developed by Katz and Kahn (1966). Pasmore and Sherwood (1978) characterized STS as organizationally complex, which recognizes the interaction between human and technology in a work environment. Systems theory view the organization as an agency that transforms a variety of inputs into positive or negative outputs. Traditional STS, identify three elements within this broader system context: technological subsystem, personnel subsystem, and work system design consisting of an organizational structure and managerial processes. Kleiner (2006) focused on the interactions in an STS in terms of hardware and/or software, internal environment, external environment, and/or an organizational design. There are studies that utilize STS to understand and optimize the relationship between humans and the built environment. Kleiner et al. (2008) and Zhao et al. (2016) use STS breakdowns that contribute to accidents on construction sites. Viewing zero energy housing as STS enables researchers and practitioners to create the systems view of zero energy, which identifies subsystem relationships enabling the goal setting for zero energy housing operational effectiveness.

Residential Energy Simulation

AEC professionals utilize simulations to predict building performance. Simulations help designers understand the impact of design changes and synthesize the interaction of complex subsystems toward total system performance. Based on the relevant literature, authors' understanding of relative market penetration and their experience developing residential energy simulations; three residential simulation tools were evaluated for this study.

BEOPT: In 2011, the DOE's National Renewable Energy Laboratory (NREL) released BEopt (Building Energy Optimization) to the public. BEopt was developed with the intent of providing HPH practitioners with a method for comparing costs, energy savings, and interactions of energy efficient technologies toward the development of zero energy housing (Anderson, R., Christensen, C., & Horowitz, S., 2006; Christensen, C., Anderson, R., Horowitz, S., Courtney, A., & Spencer, J., 2006). BEOpt is a dynamic, hourly simulation tool that utilizes TYM3 (Typical Meteorological Year 3) data. The cost optimization, energy efficient technology libraries and occupant behavior parameters provide the practitioner with a robust, yet efficient tool set for simulating zero energy buildings.

HOME ENERGY SAVER: In 2010, the DOE's Lawrence Berkley Laboratory (LBL) developed Home Energy Saver (HES), a web-based software platform. HES is a residential building energy labeling and asset rating method that uses a simplified and standardized energy assessment process. The interface is designed to support the existing homes energy analysis marketplace. HES allows for detailed occupant-technology parameter and schedule manipulation. (Bourassa, N. J., Rainer, L., Mills, E., & Glickman, J., 2012). Parker, et al. (2012) found that averaged across groups of homes, HES predicts energy use within 1% of actual consumption when behavioral inputs match actual conditions.

REMRATE: Residential Energy Services Network (RESNET) developed the Home Energy Rating System (HERS) Index. An output and major industry application of REM/Rate software is the assessment of a HERS Score. In 2015, 38% of new homes in the U.S. received a HERS Score (Elam, 2016). REM/Rate is a proprietary, asset rating, and static simulation tool used by AEC professionals, specifically HERS Raters, to rate building performance of a modeled home compared to a theoretical reference home that has the same conditioned floor area, massing, and enclosure surface areas. CS-ZE's design team utilized unit-level REM/Rate models as the primary zero energy simulation tool. It is important to note REM/Rate is not the only energy simulation tool for residential buildings available to practitioners, but its market penetration, as well as the Department of Energy's (DOE) Zero Energy Ready Program adoption and application for simulating net-zero in the literature suggests its relevance (Christian et al., 2006; Thomas and Duffy, 2013).

Beyond the generation of a HERS Index, REM/Rate can be used to prioritize energy efficiency measures during design (Sawhney et al. 2002). REM/Rate estimates annual heating, cooling and consumption loads for operation as well as estimated annual costs based on local utility rates and TMY3 weather data. One limitation of REM/Rate observed by the authors is the static nature of its occupant behavior patterns.

ANALYSIS

Apartment-level energy use and generation data were recorded at 1-hour intervals from January 2015-January 2017 and compared to apartment-level REM/Rate simulations. Table 2 provides an overview of the simulated energy use, measured energy use and the measure of error between simulated and measured results across the sample.

Standard deviation of the errors:

$$\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(e_i - \overline{e})^2}$$

mean value of errors:

$$\frac{\Sigma_{i=i}^{n} e_i}{n}$$

Table 2. Energy use overview

Unit	Actual Use kWh/yr	Generated kWh/yr (solar pv)	Net-Measured kWh/yr	REM/Rate Simulation kWh/yr	Difference kWh/yr
A	6,775	5,617	1,158	-15	1,172
B	2,299	5,480	-3,181	-235	2,946
C	5,467	4,887	580	499	81
D	4,936	4,763	143	587	444
E	6,152	5,052	1,100	147	953
F	5,734	4,943	791	117	674
G	4,840	5,216	-376	29	405
H	4,711	5,282	-571	88	659
Total	40,914	41,270	-356	1,217	Diff. 1,573
Sample Mean	5,114	5,158	-45	152	917
Sample Std Dev.	1,338	292	1,332	269	886

Note: Measurement period for analysis was 1/14/2015-1/13/2016, addresses were removed and randomized for resident privacy

Following the evaluation of apartment-level energy use, generation, and REM/Rate simulation differences, the authors recognized a need to further unpack the variability across the sample. The solar generation and REM/Rate simulations were consistent from unit to unit, but the actual use was highly variable across the eight apartments. To better understand the source of the variability, additional simulations (Table 3) were run and compared to the measured data. A RESNET HERS Rater completed the BEOpt, Home Energy Saver, and REM/Rate simulations.

Table 3. Zero energy simulation overview

Simulation	Developer	Simulation Version	Simulation Type	Simulation Standard	Simulation Platform
BEopt	NREL/DOE	v2.7.0.0	Dynamic, hourly	ANSI/ASHRAE Standard 140-2011	EnergyPlus, download
Home Energy Saver	LBL/DOE	2017	Semi-dynamic, annual	ANSI/ASHRAE Standard 140-2011	DOE-2, web-based
REM/Rate	NORESCO	v15.3	Steady-state, annual	ANSI/ASHRAE Standard 140-2011	RESNET, download or web-based

During the development of the simulations, the authors applied consistent occupant parameters where possible. Simulation defaults were utilized when specific occupant parameters were not known or available.

RESULTS

Climate Impacts

To assess the impact of year-to-year weather variances, during the measurement period, a review of heating and cooling degree days over the past decade was conducted for Richmond, VA (Figure 1). The HDD were close to the 10-year average during the first year. In the second year, CS-ZE observed slightly colder winter months. In terms of cooling, CS-ZE was exposed to less heat over the two years period compared to the average over the past decade.

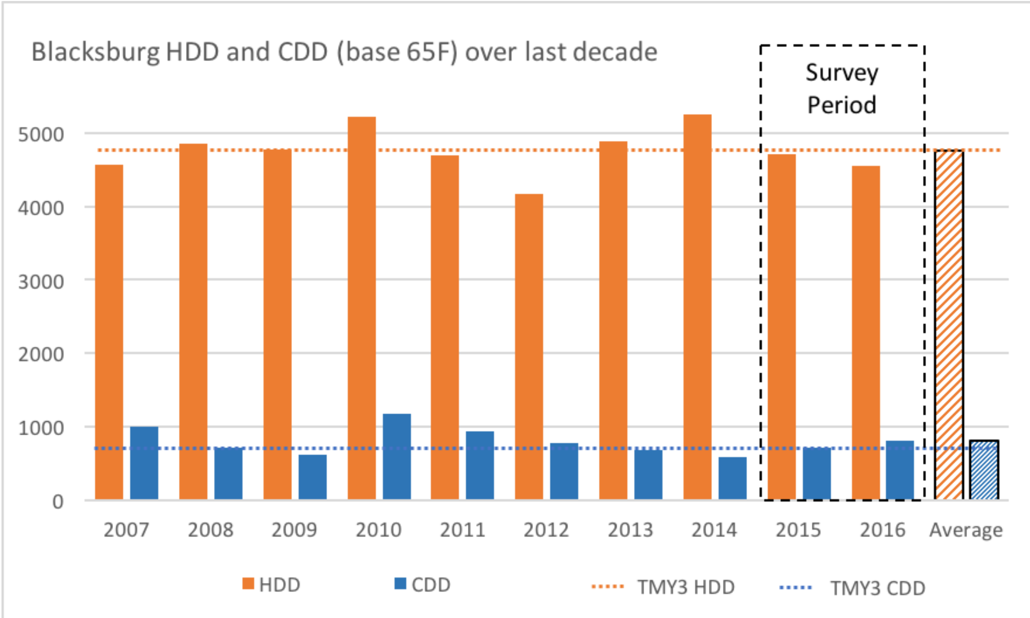

Figure 1. Comparison of Heating Degree Days and Cooling Degree Days (65°F/18°C Base) over the past ten years at the case study location in Blacksburg, VA

Next, we evaluated the relationship between circuit-level energy use, solar PV generation, and HDD/CDD (65°F/18°C Base). Figure 2 integrates the proportion of Heating Degree Days to Cooling Degree Days in Blacksburg's mixed-humid climate. Data suggest, March-October are critical months in zero energy housing in mixed-humid climates, since solar PV generation is higher than monthly end-uses. The authors were surprised that dryer energy use was higher than water heating energy use for nine out of the twelve months. Occupants in the sample tend to cook more with their range during the fall (October, November and December) and use their microwave for the balance of their cooking needs (reflected in MELs - Figure 2). The authors acknowledge that this could be a reflection of the occupant population (senior).

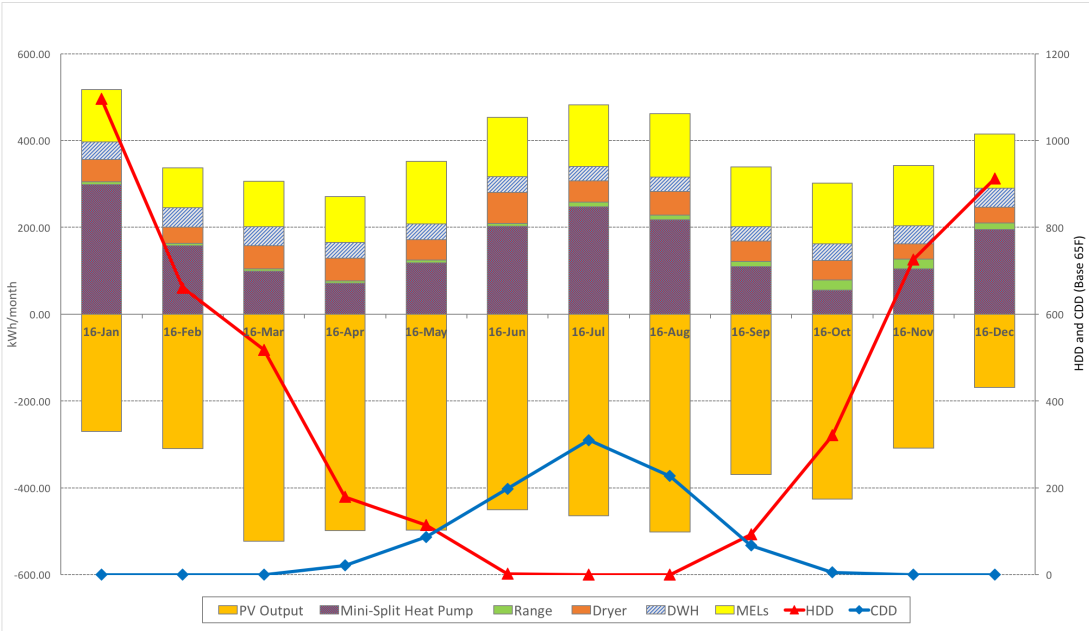

Figure 2. Monthly circuit-level energy use, solar PV generation and HDD/CDD (65°F/18°C Base)

Simulation Comparison

To understand the accuracy and precision of commonly used residential simulation programs often utilized in the design of zero energy housing, a comparative analysis was conducted. Figure 3 provides an overview of the simulation results from BEopt, Home Energy Saver, and REM/Rate. The unit-level simulations were then compared to CS-ZE's average measured end-uses. All of the simulations underestimated energy used for space heating and overestimated the energy used for air conditioning, which again could be attributed to the specific occupant demographic. REM/Rate simulated the smallest difference (23 kWh/yr) between modeled and measured space conditioning performance. CS-ZE utilizes an air to water heat pump water heater. These systems have three operating settings; 1) *Hybrid Mode* (manufacturer recommended setting), 2) *Efficiency Mode* (most efficient) and 3) *Electric Mode* (least efficient). None of the simulations analyzed provide multi-modal modeling of air to water heat pump water heaters. BEopt underestimated the water heating energy use by 93 kWh/yr and REM/Rate overestimated water heating by 189 kWh/yr. It is important to note, that while Home Energy Saver provides options for an occupant-water heater schedule and additional use parameters, it currently does not support modeling of air to water heat pump water heaters. This is a limitation of the program's use in zero energy housing design, since this technology is a common application in all-electric zero energy housing projects.

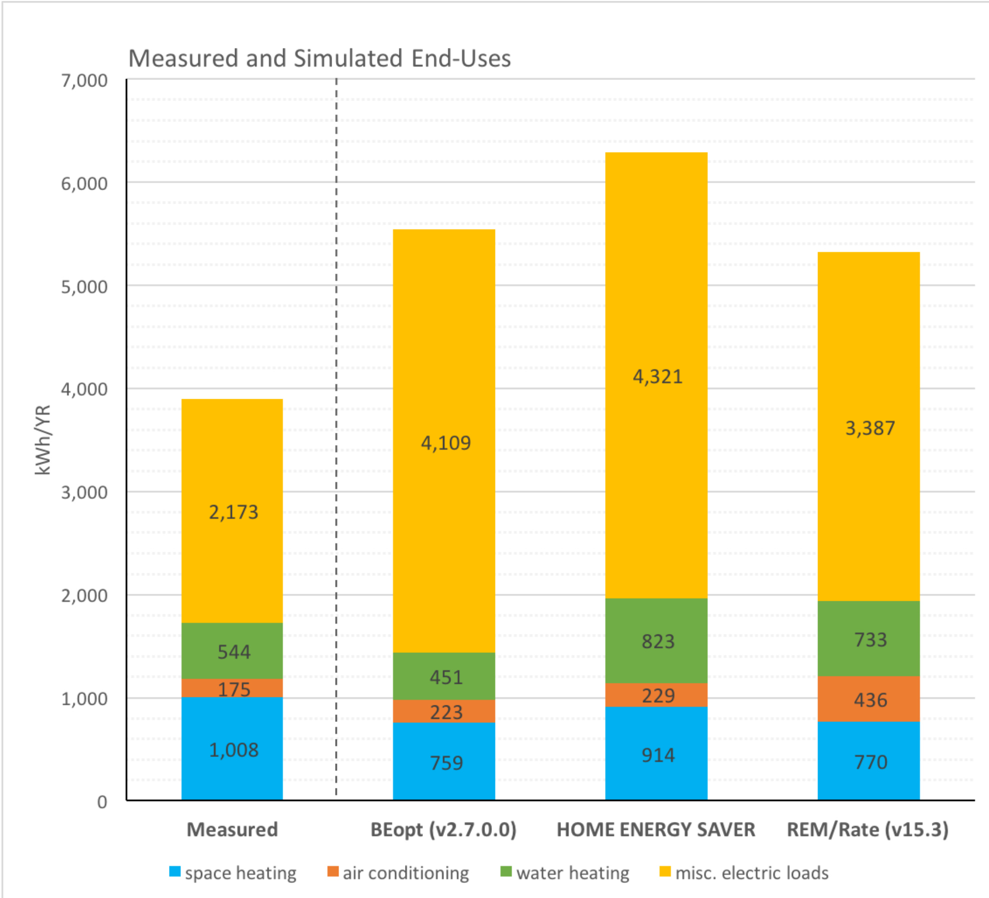

Figure 4. Measured and Simulated end-use comparison

The researchers were particularly interested in the variances of MELs (lighting, small and large appliances) when compared between simulations. All three simulation tools overestimated the impact of MELs on annual energy use. REM/Rate was the most accurate of the simulations, but overestimated MEL energy use by 35% (or 1,214 kWh/yr).

Discussion

The difference between simulated and measured MELs and water heating (measure of error) should be concerning to builder-developers and designers engaged in the development of zero energy housing. The misalignment between expected and realized performance creates uncertainty and risk for housing practitioners. Poor building performance due to sub-optimal building enclosure and/or space conditioning systems rests on the design team and/or builder-developer. MELs and water heating are occupant driven loads, yet designers and/or builder-developers could be blamed for poor performance as we produce more zero energy housing. The authors propose a human factors-based socio-technical system model (Figure 5) to begin to close the post-occupancy performance gap, improve occupant (user) experience and reduce risk for AEC professionals producing zero energy housing.

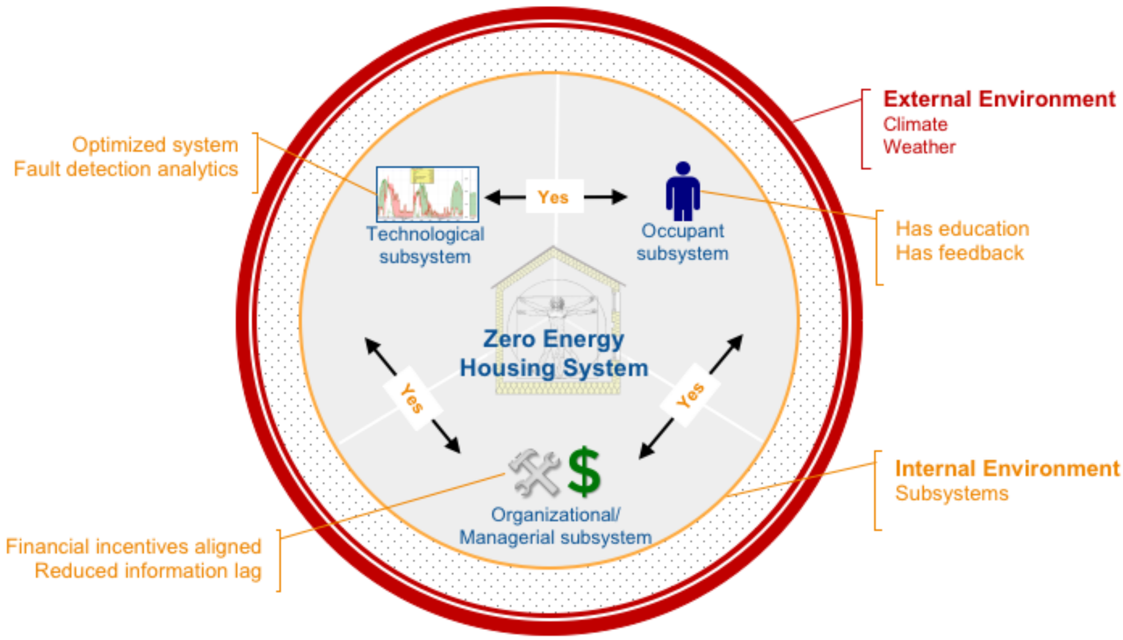

Figure 5. Zero energy housing socio-technical systems are comprised of the 1) occupant subsystem, 2) technological subsystem, 3) organization/managerial subsystem and 4) external environmental factors

Builder-developers represent the *Organizational/Managerial* subsystems in the zero energy housing STS. Their design and construction approach is appropriate for the external environment of development (e.g. climate and weather). They must structure the development to foster financial incentive alignment for themselves as well as the occupant. They do not rely on traditional utility billing technology to understand the performance of their system; this would create an informational lag. Human-factors researchers have reported that people are generally poor at managing systems with lags in information and delayed feedback loops (Brehmer, 1992; Sterman, 1989). In the zero energy housing STS, energy monitoring systems are installed in each unit to report energy use in real time using an In-home Display (IHD) for occupants. Cloud-based platforms would be monitored by building managers for performance reporting and system failure alerting. Studies have shown that IHDs have improved behavior towards a more energy efficient lifestyle and resulted in 10-15% monthly energy use reductions provided it was: a) given frequently; b) provided over long periods of time; c) with appliances broken out individually; d) presented in clear, appealing ways; and e) utilizing computerized, interactive tools. (Stinson et al. 2015; Ouyang & Hokao 2009; Fischer 2008). Reducing informational lag while at the same time educating the *Organizational/Managerial* and *Occupant* subsystems is a critical next step. Recent work from the authors that examined resident energy use and survey response on behavior in HPH. Occupants with education on HPH apartments had a lower average energy usage monthly and annually (over 3 years) by almost 14.8% (or 1,114 kWh/yr) compared to occupants that reported having not received education on their HPH apartment (McCoy et al. 2017).

The *Technological* subsystem is the result of designing, simulating, constructing and commissioning zero energy housing technologies. As demonstrated in the analysis in this paper, CS-ZE has an optimized *Technological* subsystem capable of delivering zero energy performance. It is important to recognize that monitoring and maintaining these systems may still result in the broader system performance falling short of its operational performance goal. For example, in January 2017, a heat pump failed in a unit at CS-ZE. The enclosure was robust enough that there was not an immediate maintenance call (e.g. freezing pipes, cold residents). The heat pump was not operational for six weeks and the resident used an electric resistance space heater to maintain comfort, thus jeopardizing the zero energy performance goal of the development. Each apartment at CS-ZE has an energy monitoring system, but there was not a trained, human-monitor or fault detection system to alert the responsible party within the *Organizational/Managerial* subsystem. In the proposed zero energy housing STS, monitoring systems would also be equipped with fault detection analytics to define operational effectiveness goals and send an electronic alert (e.g. email, text) to the responsible party when there is a *Technological* subsystem failure.

Further Work

Following the results of the comparative analysis of simulation tools the authors suggest software developers consider integrating STS parameters into their simulations to reduce the gaps in existing tools for AEC professionals. Parameters for software developers to consider include, but are not limited to: financial incentive alignment, physiological-based and occupancy schedule parameters based on quantitate and qualitative data collection methods to improve their usefulness to zero energy housing practitioners. The authors are furthering research in this area by deploying IHDs and educational interventions to residents and building managers.

Limitations

It should be noted that it is not the intent of the authors to test and report the value of the four simulation tools discussed in this paper, but rather provide practitioners with feedback regarding measured versus simulated results that may be impacted by STS. A better understanding of STS could result in closing the post-occupancy performance gap in zero energy housing systems.

CONCLUSION

This study reported findings from a zero energy rental housing development that provides housing for seniors (55+ years old). The results support the need for an increase in model accuracy for high performance housing (HPH) in terms of occupancy context and suggest a human factors-based socio-technical system model to close the post-occupancy gap in zero energy housing. The authors developed the follow conclusions as a result of this work:

- Post-occupancy measurements through the use of IHD-based monitoring systems with fault detection analytics of zero energy housing projects are critical to meet and maintain zero energy housing operational performance effectiveness goals.

- AEC professionals can utilize measured data to calibrate and compensate for the error in simulating zero energy performance with existing residential simulation tools.
- Common residential simulation tools struggle to predict water heating and MELs in zero energy housing. As we race to zero energy housing, builder-developers and designers are at risk due to since MELs are occupant-driven loads.
- Poor building performance due to sub-optimal building enclosure and/or space conditioning systems rests on the design team and/or builder-developer. MELs and water heating are occupant driven loads, yet designer and/or builder-developers could be blamed for poor performance, as we produce more zero energy housing.
- Understanding and refining zero energy housing STS may result in operational performance effectiveness goals being met, reduced risk for builder-developers, and greater occupant satisfaction.

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Impact of Occupant Behavior in Data-driven Energy Use Modeling in Diverse Residential Buildings Across Multiple Climates

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ABSTRACT

Data-driven, inverse modeling is often used for the estimation and prediction of energy consumption of residential buildings. Yet in contrast with commercial buildings which typically follow a more regular occupancy schedule, the occupant behavior in residential buildings can be much more varied both over time in a single home, and across different homes. This includes some homes with very regular and very irregular occupancy schedules and use patterns of the energy-consuming building systems. As a result, this can make the development of an inverse modeling method that is able to predict residential energy consumption across a diverse residential dataset challenging. In this research a modified change-point modeling method is used to fit inverse models to monthly energy use data from a diverse set of more than 1000 homes in four different cities in the U.S. located in climate zones 2A, 3A, and 5A. It was found that across the different cities of study, 3 to 28% of homes, depending on the location, do not fit the typically recommended criteria for model acceptance. Further analysis determined that between 0.2% and 12.5% of models have specific data points that do not follow the trends of the majority of the energy use data, and significantly impact model performance. To determine the reasons for unpredictable energy performance and lack of model fit, highly-granular, 1-minute and hourly interval disaggregated electricity data was then analyzed. In most of these homes with a wide variation in use, particularly during the holiday season in winter months, outlier months have significantly different occupant behavior-dependent energy end uses, such as HVAC, large appliances such as for cooking, lights, and electrical plug loads. The improved understanding of inverse model performance for residential buildings and the reasons for lack of fit and occurrence of outliers helps to drive improved inverse modeling methods to predict energy use for residential buildings.

INTRODUCTION

Among the many influencing factors impacting the energy use of buildings, the impact that occupants and their behavior has on the energy use of a residential building is significant (Hong 2016). As the modern building stock continue to benefit from opportunities to improve efficiency, particularly in the face of climate change challenges, better quantifying the impact of occupant behavior on building energy is paramount. Occupants can both positively and negatively impact the energy efficiency of a residential building, and, overall in comparison to a commercial building, have a more significant impact. Specifically and most importantly, occupants govern the controls of the buildings' heating, ventilating, and air conditioning system. HVAC systems are used in nearly 90% of U.S. homes nationwide, and nearly 100% in hot climates such as Texas (U.S. EIA 2015), and also represent approximately half of the energy use consumed overall in residential buildings (U.S. EIA 2015). Occupants decide what setpoint to set the thermostat at for conditioning their home. Depending on the building size and location, a single degree difference in thermostat setpoint in the cooling season can mean a 3-5% increase in energy use (Sundaravadanam 2017). Secondly, occupants determine the internal loads in a building. This includes heat and moisture gains from occupants themselves, as well as from electronics, appliances, computers, and other energy consuming devices that are dependent on occupants to operate. Higher internal loads in summer increases both overall plug loads, and also increases HVAC use. More indirectly, occupants also have control of whether or not windows and doors are open and thus overall building air exchange rates, as well as whether or not a building and its HVAC system is maintained properly. Thus, whether indirectly or directly, occupant behavior is highly important to a building's overall energy consumption, and deserves significant attention.

In recent years, it has become more recognized that occupant behavior and its impact on building performance, in particular in residential buildings, deserves significant further study. A number of recent studies have discussed and summarized many of the latest findings in this area (Leiwen et al. 2013, Hojjati et al. 2012, Rhodes et al. 2014). Many studies have focused on improved modeling of occupant behavior in energy modeling programs that is more representative than the nearly static use patterns of occupant behavior currently used; others have observed occupant behavior in households with the goal better characterization of occupant behavior impacts. Many of the studies that focus on the use of real, measured energy use and/or occupant data, however, are conducted on a smaller number of homes, given the time and cost involved with data collection. Therefore despite these efforts, better understanding household energy use patterns still has a large potential to be improved (Kowsari et al. 2011, Wiesmann et al. 2011). Thus overall, the current literature lacks an overall analysis of the impact of occupants on energy use across a larger number of homes and varying climate regions. This is particularly important given the known significant impact of climate conditions, and in particular temperature, on energy use and occupant use patterns (Hojjati et al. 2012, Yun et al. 2011, Parker 2003, Perez et al. 2017). This type of analysis is needed to determine the level of variability in energy use that can be characterized as being due to occupants.

Therefore in this research we have gathered datasets of residential energy use data from four different regions of the U.S., including three ASHRAE climate zones, to better characterize the variability associated with energy use, much of which can be attributed to occupant behavior. For the Texas dataset, where the most detailed information is available, both at a higher frequency and disaggregated circuit-level information for many of these homes, the specific occupant energy-using behaviors that create the highest levels of variability are studied in further detail. By better understanding these significant influencing factors of energy use, we can understand how to better develop methodologies to predict energy use of buildings taking into account occupant behaviors and the associated level of variability in energy use to expect. This includes for a typical house, as well as those that that demonstrate extremely unreliable and highly reliable energy use patterns. This is important both for building energy modeling (i.e. forward modeling), as a level of variability in occupant behavior is assumed in an energy model, but may not be consistent with actual levels of variability for real homes, and for inverse models, which rely on mostly statistical-based approaches to predict consumption.

METHODOLOGY

The methodology for identifying the impact of occupant behavior in inverse models of monthly energy use from diverse residential buildings in four different cities in the U.S. located in climate zones 2A, 3A, and 5A is demonstrated in Figure 1. This flowchart includes five steps: (1) Data collection of energy usage of residential buildings in multiple climate zones, (2) Development of inverse models for each residential building in the datasets, (3) Checking of the standard deviation and outliers in inverse models, (4) Identification of the impact of occupant behaviors in residential buildings through the study of outliers in the inverse models. Each of these steps is discussed in further detail in this section.

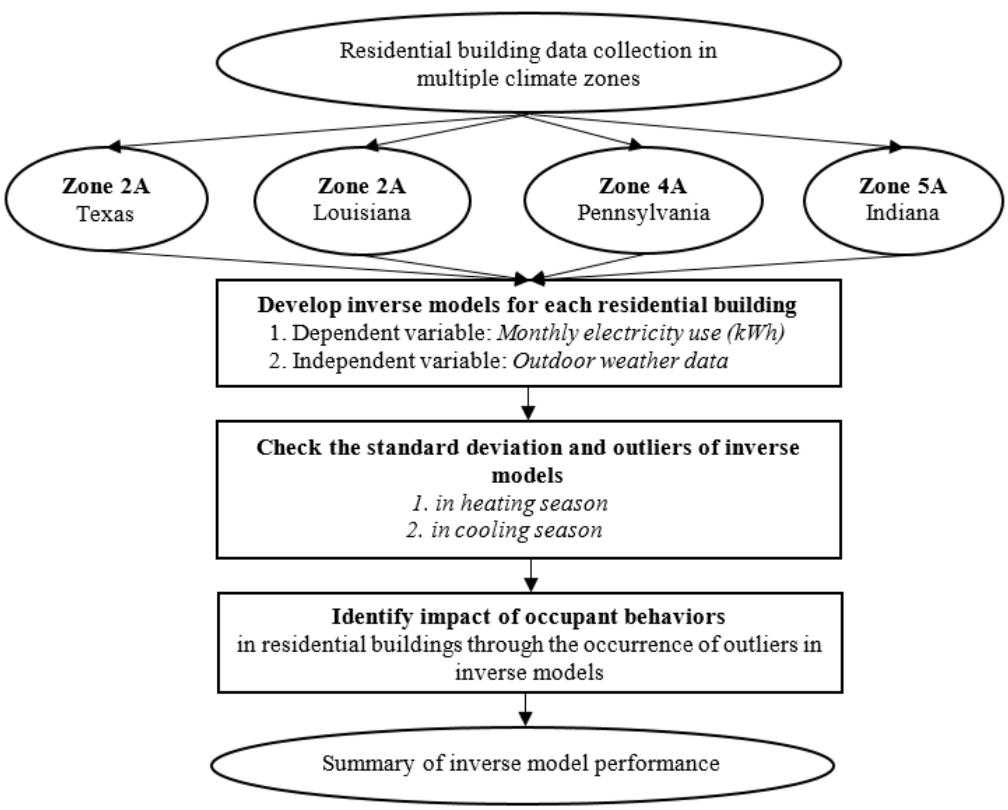

Figure 1. Methodology for identifying the impact of occupant behavior in inverse models of residential building energy use across multiple climate zones

(1) Residential building data collection in multiple climate zones. Data is collected from 1000 homes in New Orleans, Louisiana (ASHRAE Climate Zone 2A (ASHRAE 2013)), 1541 homes in the Houston and Austin, Texas areas (Zone 2A, hot-humid), 102 homes in Philadelphia, Pennsylvania (Zone 4A, mixed-humid) and 1000 houses in northern Indiana (Zone 5A, cool-humid). Overall information on the residential building stock in these climate zones is collected (U.S. EIA 2015). This data includes average age of household, number of occupants, number of bedrooms, area, age of residents, level of education, and household income (Table 1).

Table 1. Residential building characteristics in studied ASHRAE climate zones

Categories	United States	Texas & Louisiana (Zone 2A)	Pennsylvania (Zone 4A)	Indiana (Zone 5A)
General building characteristics				
House ownership *(%)*	63.0	62.7	66.0	63.9
Average number of bedrooms	2.7	2.7	2.8	2.7
Occupant characteristics				
Avg. age of household (*yrs)*	51.9	53.8	52.3	51.1
Number of occupants *(avg.)*	2.5	2.5	2.5	2.5
Children under 18 *(%)*	32.0	31.1	31.1	31.8
Total annual household income				
Under $60,000 *(%)*	57.8	61.4	57.5	58.9
$60,000 - $99,999 *(%)*	21.2	21.1	23.6	18.8
$100,000 - $139,999 *(%)*	11.5	9.6	11.8	11.3
$140,000 and over *(%)*	9.5	7.9	7.1	11.0
HVAC system characteristics				
Air conditioning *(%)*	87.2	94.4	85.6	94.3
Central air conditioning *(%)*	65.2	81.6	56.4	70.2
Electric heat *(%)*	36.2	64.9	41.7	19.3
Gas Heat *(%)*	47.2	22.8	42.8	62.1
Programmable Thermostat *(%)*	41.0	46.9	41.7	36.6

Note: all data from RECS 2015 dataset (U.S. EIA 2015); electric heat = all electric-using heat sources; gas heat = natural gas; Zone 2A = hot-humid, Zone 4A = mixed-humid; Zone 5A = cool-humid

The characteristics of residential buildings in the U.S. overall is also included in the Table 1 for a basis of comparison to the locations of study. Generally, the characteristics of the residential buildings and households in the different locations of study are similar. Approximately two-thirds of buildings are owner-occupied, with 2.7 to 2.8 bedrooms on average per home. In terms of occupants, the average number is 2.5 people across all climate zones, including approximately one third of which have children; the majority of homes make less than $60,000 per year. Most importantly, for this study, however, is the difference in HVAC system types across the studied locations, as these systems are the largest consumers of energy in residential buildings in the U.S., and are highly dependent on occupant-created internal loads, and occupant-set thermostat setpoints. The hot and humid climate zone (Zone 2A) has the highest percent of homes with air conditioning, and also relies more heavily on electricity-using heating systems due to the milder climates not requiring strong heating systems. The mixed climate zone location (Zone 4A) also has a high penetration of air conditioning, and homes use a nearly even split between electric and gas-powered heating systems. In the studied cool climate (Zone 5A), most homes use both air conditioning and gas heat, given the significant heating and cooling demands in this location. Residential electricity use data collected in the above-described locations includes monthly electricity use data for each home. The data was quality controlled to ensure that all data utilized was measured, rather than estimated data, and also that the consumption data recorded provided a reasonable value, following the methods suggested by Cetin et al. (2015). Electricity use data was also normalized to an equivalent number of days across all months, to ensure the same amount of time was utilized for consumption in each of the data points. To provide a characterization of the energy use of the studied homes, a distribution of electricity use per month across all of the homes in each dataset is provided in Figure 2. The data time periods vary by dataset based on available data, but generally span the period of 2014 to 2016. This includes 12 months in Texas (May 2014 to April 2015), 14 months in Louisiana (November 2014 to December 2015), 10 months in Pennsylvania (April 2015 to January 2016), and 16 months in Indiana (January 2015 to April 2016) respectively.

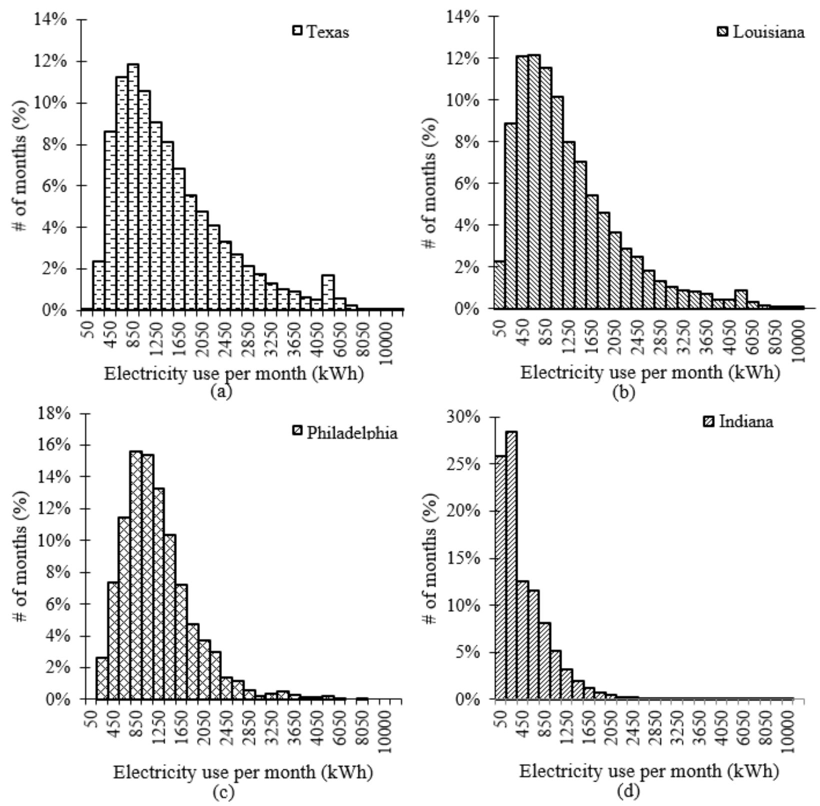

Figure 2. Monthly energy usage of residential buildings in each studied location, including (a) Texas, (b) Louisiana, (c) Pennsylvania, and (d) Indiana. *Note: The consumption bin of 5050 kWh/month in each of the charts is relatively larger than those intervals below this bin; this is done for graphing purposes only to provide more readable graphs for this figure.*

In general, across all studied months, the residential buildings in Pennsylvania have the highest average monthly electricity use among the four locations, including an average of 1,134 kWh/month, and 31% of homes from 850 kWh to 1250 kWh (Figure 2c). The distributions of monthly electricity use in Louisiana and Texas (Figure 2a and 2b) are similar, with slightly lower average values, but with similar median values of 1,164 kWh and 906 kWh respectively. Indiana has the lowest overall energy use per household, likely due in part to the lower percentage of homes that use electricity-using heating systems, and due to the relatively lower need for air conditioning in the summer in this location as compared to others. In the studied Indiana dataset, approximately 53% of the data included months where under 450 kWh of energy was consumed (Figure 2d). These electricity use data are used to develop inverse models of electricity use for each residential building.

Additional data used in this study includes weather data. For the development of inverse models in Step 2, the average monthly weather data, including outdoor temperatures, are collected from weather stations nearby the residential buildings, the majority of which are located at local airports. The weather datasets utilized are subjected to similar quality control checks to that of the energy use data.

(2) Development of inverse models for residential buildings. Among the many models that have been developed in recent years, this research uses a single-variate model to develop inverse change-point models for each residential building with the monthly energy use data as the dependent variable and average outdoor temperature as the independent variable. Given the number of monthly datapoints per home (10-14 datapoints per home) in the utilized datasets, a single-variate model is statically appropriate (ASHRAE 2013) as compared to more complex multi-variate models. In addition in comparison to other more complex methods, as pointed out by Zhang et al. (2015), change-point models are among the simplest models and perform similarly to the more complex models have been developed in recent years (Zhang et al. 2015). Initial checks were conducted to determine the most appropriate and most significant single variable among the collected weather data. Overall, the outdoor temperature was determine to be the most appropriate and significant predictor as compared to humidity, wind speed and solar radiation across the dataset, and thus was used for this research.

Inverse change-point models represent a family of model types, depending on the trends found in the data in relationship with outdoor temperature. These model types include five, four, three, and two-parameter change-point cooling and/or heating models (ASHRAE 2013, Kissock et al. 2003). Each inverse change-point model has a base temperature called as a balance-point temperature that minimal energy/electricity use is required for heating or cooling and to make the comfortable condition in a building (ASHRAE 2013). This base temperature represents the transition between the heating and cooling seasons. A base temperature in each house is automatically identified using a custom algorithm for developing inverse change-point model using Matlab. The algorithm used to complete the inverse change-point model for each residential building includes tests to check the fit of inverse model was developed building off of the methods presented in Paulus et al. (2015), including the use of four different minimum criteria that must be achieved for a particular change-point model to be determined to be an acceptable fit. These include the shape test, significance test, data population test, and goodness of fit test. For the shape test, the developed model must follow appropriate slopes of regression lines in the inverse change-point model, including in winter, a near-flat or negative slope, and in summer, a near-flat or positive slope. The significance test requires a threshold p-value of 0.05 for the predictor variable(s); the data population test requires at least three data points in each portion of the model to be considered acceptable. The final test is goodness of fit, or R^2 test; in this case a threshold of the coefficient of determination is set to be 0.5, following similar levels used by the U.S. EPA for the EnergyStar building program which requires a minimum of 0.4 for the R^2 value (Energy Star 2015). If all of four tests are satisfied, one final type of inverse change-point models are determined. The order of checking for fit of all criteria begins with the most complex model (5-point model), and becoming decreasingly complex until a model is determined to meet these four criteria. If all four criteria cannot be met then the studied home is determined to have "no model" that fits using this methodology.

(**3) Check the standard deviation and outliers of inverse models in the heating and/or cooling seasons**. In modeled energy use data of residential building there is very minimal dispersion of the energy use data from the predicted values from inverse models (Sundaravadanam 2017). In comparison the real datasets studies have, in some cases, significant dispersion of the data, much of which is likely due to the variability in occupant behavior. To check the dispersion of the data points in the inverse models, the standard deviation method is applied (Seo 2006, Rousseeuw et al. 1987). The standard deviation is based on the residual values between actual and predicted electricity use in the inverse model of each residential building. The standard deviation method assumes a normal distribution of residuals, which has generally found to be the case in change point modeling methods of the real residential energy use data. Next, the value of the standard deviation in the heating and cooling season for each climate zone is determined. These values help to check the ability of the inverse model to predict energy use, as well as to identify potential outlier data points that are used in the proposed method.

To determine the presence of energy use data outliers the standard deviation values are used. The use of the standard deviation is one of the most commonly recommended methods used in energy performance contracting and in measurement and verification (M&V) activities (M & V Guidelines 2011) to determine the presence of outliers. Both data points in heating and cooling seasons, depending on the type of inverse model, are checked for outliers. The occurrence of these outlier data points can impact the type of models that best fit the data as significantly impact the evaluated accuracy of models predictions.

(4) Identify impact of occupant behaviors in residential buildings. The impact of occupant behavior in residential buildings are determined through the study of the occurrence of outliers in the developed inverse models. The behavior associated with the use of electric end-uses and occupant-dependent HVAC use can be clearly determined through the analysis of more frequent 1-minute interval energy use data of whole home electricity use and individual disaggregated end-uses. The occurrence of outlier data point(s) in the inverse models determined in Step 4 is used to identify those points in time that merit further study of the electricity use of all electricity-consuming end uses at a 1-mintue level frequency. With this 1-minute level electricity data, the time-of-use, frequency of use, and/or the total electricity use of each end-use can clarify the specific influencing factor(s) that have most significantly contributed to the high levels of variation represented in a data point(s).

(5) Summary. The results from the study are finally compared among climate zones, including the inverse model performance and the number of outliers that are detected. For the result of impact of occupant behaviors, it is further studied for homes in Climate Zone 2A as this Texas data is the only dataset where 1-minute level of electricity use data is available. More specifically, impact of occupant behaviors in Texas are analysis through several case studies.

RESULTS AND DISCUSSION

As introduced in the methodology section, homes with weather and energy use data available in Louisiana, Texas, Pennsylvania, and Indiana are studied. Data on energy use is combined with average outdoor temperature data, and used to develop the inverse change-point models for each residential building in these locations. Table 2 is a summary of the number of inverse change-point models developed in each location’s data. It is noted that there are a number of houses that do not have models because, as explained in the methodology, these homes have not met the requirements of the four test criteria for any of the change model types. The developed inverse models are diverse, including four-, three-, or two-parameter change-point heating/cooling models. Examples of inverse change-point models are shown in Figure 3.

The number type of models (Table 2) and the distribution of base temperatures (Figure 4) in each location reflects the features of the climate in which those homes are located. Texas has a hot-humid climate, therefore it is reasonable that the number of three parameter change-point models is highest among four locations (59.2%). A 3-paramter model is most likely associated with a home that uses air conditioning in the summer and either little to no heat in winter, or uses gas heat. Pennsylvania has the highest number of 4 parameter inverse models (63.7%), compared to other types of models in this location. Pennsylvania is located in a mixed climate with cold winters and hot summers, and, on average, approximately half of the building stock using electricity for heat (Table 1). A four-parameter model is typically associated with homes that use electricity for both heating and cooling, thus the significant number of homes with this type of model seems reasonable, although slightly higher than expected given the even split of gas and electric heated homes in this location. Also in Pennsylvania, 10.8 % of houses have a three parameter change-point heating model, which is the largest number among the four locations. The three-parameter heating model is typically associated with homes with no air conditioning equipment but with electric heating equipment. Given that Pennsylvania’s building stock in this climate zone has the lowest percentage of homes with air conditioning (85%) among those studied, this higher percentage of homes with this type of model also makes sense. In general, most of zones have the limited number of two parameter change-point and houses that do not have any model developed. The distribution of base temperature of change-point models with the different ranges for four climate zones. With colder weather characteristics, Pennsylvania and Indiana have a median base temperatures of 16°C and 14°C respectively, while Texas and Louisiana with the hot humid weather have slightingly higher median base temperature at 19°C. This can be explained by the occupant behavior in these climate zones. For example, in warm climates occupants may be more comfortable with warmer interior temperatures before turning on the air conditioning, where as in cooler climates, higher temperatures may not be tolerated as well.

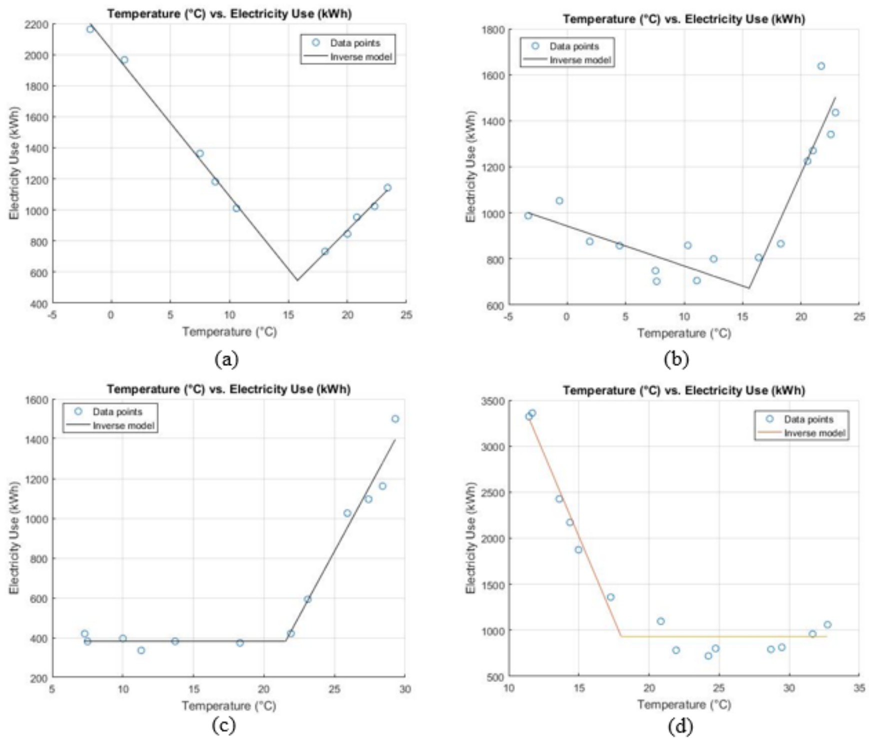

Figure 3. Examples of change-point models: (a) 4 parameter (Pennsylvania), (b) 4 parameter (Indiana), (c) 3 parameter cooling (Texas), (d) 3 parameter heating (Louisiana)

Table 2. Inverse change-point (CP) models in each climate zone

Type of models	# of residential buildings (%)			
	Texas (Zone 2A)	Louisiana (Zone 2A)	Philadelphia (Zone 4A)	Indiana (Zone 5A)
4-parameter CP	34.2 %	50.5 %	63.7 %	30.1 %
3-parameter CP cooling	59.2 %	36.2 %	11.8 %	33.7 %
3-parameter CP heating	1.0 %	2.3 %	10.8 %	6.9 %
2-parameter CP cooling	2.1 %	1.1 %	1.0 %	0.2 %
2-parameter CP heating	0.1 %	0.0 %	0.0 %	0.3 %
No model	3.3 %	9.9 %	12.7 %	28.8 %

The standard deviation of each model is next calculated. The distribution of the standard deviation in the heating and cooling seasons across the locations of study is shown in Figure 4. From this figure, it is clear that the variance of data points in heating season is larger than in cooling season. The median values of standard deviation in heating season of Louisiana, Texas, Indiana, and Philadelphia is 496 kWh, kWh, 373 kWh, and 612 kWh respectively, while the values for the cooling season are 191 kWh, 223 kWh, 157 kWh, and 155 kWh respectively. The high variance of energy consumption in heating season is consistent with the higher number of outliers that occur in heating season in comparison with cooling season. The reasons for this high variation are explored further in the following section.

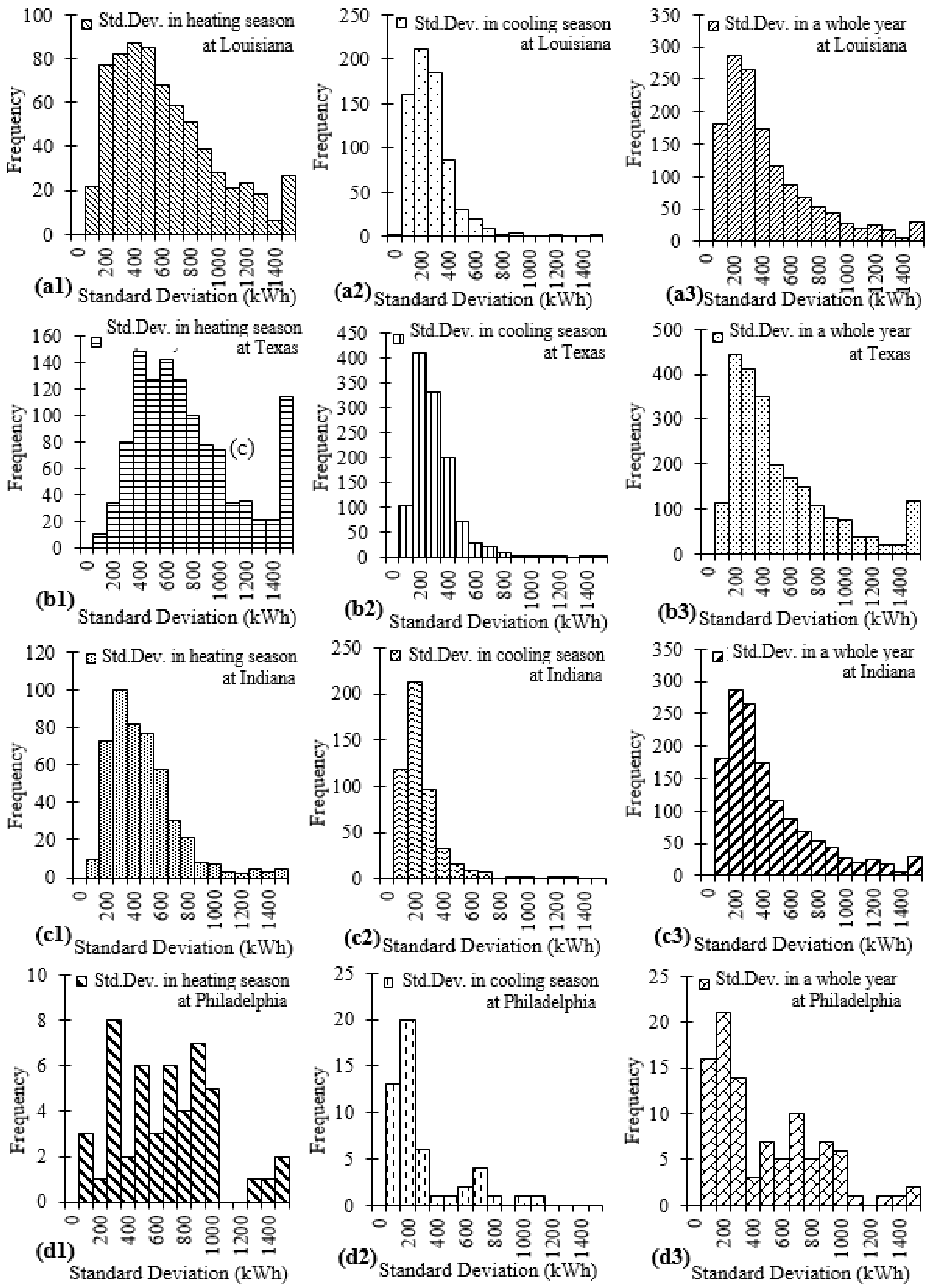

Figure 4. Distributions of standard deviation in each climate zone in the heating season (a1-d1), in the cooling season (a2-d2) and in the entire year (a3-d3)

To check the outliers in the inverse models, the value of 1.5 standard deviation is used. This threshold is chosen based on the comparison of several methods of outlier detection such as the quartile method and Grubbs' test, to ensure the chosen value for outlier detection is equivalent to among common methods. In the quartile method, the equivalent value to 1.5 is used in the calculation of the interquartile range to establish the lower and upper fence (Tukey 1977). Table 4 shows the number of outliers detected in the inverse change-point models in each location of study using this threshold.

Table 4. Summary results of outliers detected in each location of study

Zone	Number of outliers (%)	
	in heating season	in cooling season
2A - Louisiana	1.6 %	0.2%
2A - Texas	6.7 %	2.0 %
4A - Pennsylvania	12.5%	0.9%
5A - Indiana	7.2%	2.3%

For Pennsylvania and Indiana the outliers are distributed nearly equally across all months of the year (from 8% to 12% of total outliers for each month) while the number of outliers in December and January is larger than other months in Louisiana and Texas, accounting for 37.5% of total outliers. One reason for this occurrence is likely that these months are the popular months for vacations due to holidays, and also popular months for family gatherings or parties that include a significantly larger number of people in the home than is typical throughout the year. Additional occupants can significantly increase internal loads, and thus total electricity consumption. The second most common months for outliers across the datasets are April and May. This is likely due to the behavior of occupants in transition season such as opening door for a natural ventilation rather than turning on the HVAC system, or inconsistent HVAC use behavior depending on the outdoor temperatures. Given that transition season's HVAC use is often hard to predict as compared to the very warm and very cold portions of the year, this is not surprising.

Further study of these homes and months that are considered outliers is next merited to further understand the causes of these outliers. By using 1-minute interval energy use data, we find some evidence from houses in Texas that there were a significant increase or decrease in internal loads such as cooking appliances (e.g. oven, range, microwave, kitchen appliances), in large appliances (e.g. dish washer, clothes washer, clothes dryer), in other plug loads, and in lighting. To clarify this reason more clearly, a case study home is analyzed using the 1-minute level of electricity use data in Texas.

CASE STUDY HOME

As an initial demonstration of the underlying causes of the outliers and the associated relationship with occupant behavior, a case study home (Figure 5) is used. The monthly electricity use in the heating season, $E_{heating}$, is represented by the following model:

$E_{heating} = -21.97t_{o,h} + 764.84$, where outdoor temperature in the heating season, $t_{o,h}$, is below base temperature. Similarly, the monthly electricity use in the cooling season, $E_{cooling} = 63.49t_{o,} - 766.28$ where outdoor temperature in the cooling season, $t_{o,c}$, is above base temperature. The total energy consumption in January (788.9 kWh) is higher than the established threshold of energy use beyond the predicted value therefore, January is considered an outlier. The causes of this outlier is investigated by studying each of the end uses individually.

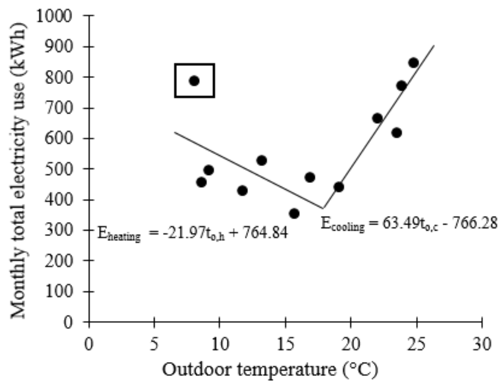

Figure 5. Inverse change-point model of the case study home *(Note: black square indicates the identified outlier)*

In terms of HVAC use, this house uses a two-stage heat pump for its HVAC system, as seen the 1-minute level electricity demand profile in Figure 6. The reported the indoor setpoint temperatures in winter range between 18.8°C and 20.6°C depending on the time of day. In January, for each of the weekdays, the HVAC is turned on to a higher temperature to warm up the home around 5:00 AM, then, the thermostat is set back to a lower temperature when the occupants leave by 9:30 AM. At approximately 4:00 PM, the HVAC setpoint is turned back up until approximately 9:30 PM. During sleeping hours, the HVAC system setpoint is lowered again. It means that there is a higher heating setpoint for approximately 10 hours, and a lower (less electricity intensive) setpoint for the remaining 14 hours in January. In other months of similar outdoor temperatures (February, December), the period of time with higher heating set point is only average 5 hours (6:00 - 8:00 AM and 5:00 - 8:00 PM). Therefore, the occupants in this house appear to be at home more in January, thus heating their home for a longer period of time. This is contributing factor to energy use differences.

The non-HVAC appliances monitored at the circuit level include the clothes washer, dryer, dish washer, multiple circuits of lights and plug loads, oven, range, refrigerator, water heater, and other appliances not included in the monitored circuits. Comparing monthly use frequency, a plug loads circuit, range, water heater, the dish washer have values outside of the set threshold level of variation in the month of January but in no other months. Figure 7 shows the lights and dish washer use as a demonstration of this difference. These plots show that the particular light and plug loads and the dish washer energy use are not dependent on temperature and have minimal variation in use, however during the month of January when energy use is higher, were used significantly more.

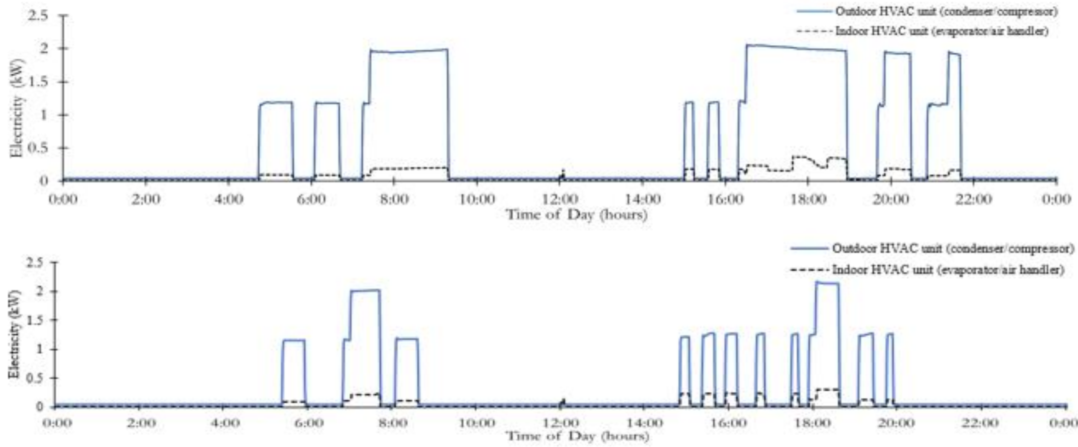

Figure 6. Representative weekday HVAC system electricity demand in most of January (e.g. 01/04/15), as compared to February (e.g. 02/04/15)

Many major appliances' electricity use and amount of time used, including the dish washer, water heater, washer and dryer, and range, among others, is highly dependent on the number of occupants and their associated behavior. Correlations developed for building energy simulation purposes are used to determine the equivalent number of occupants in this house using the following equations (Wilson et al. 2014):

$$\text{Electricity use}_{\text{dish washer/year}} = 87.6 + 49.49 \times (N_{occupants} - 0.87) \text{ (kWh/year)} \quad (11)$$

where $N_{occupants}$ is the number of occupants. January has the highest equivalent number of occupants (2.72) in comparison with the average number in this year (1.79). This is consistent with the equivalent number of occupants calculated using these empirical equations for other monitored appliances. Therefore, it is assumed that a higher number of occupants (i.e. guests) were likely occupying this home during this month.

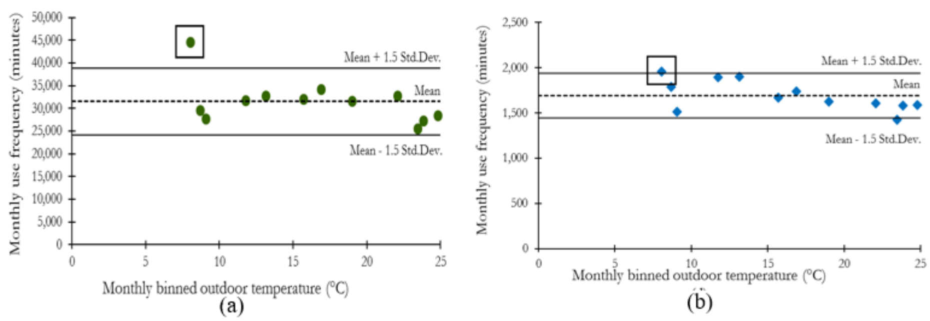

Figure 7. Monthly use frequency of (a) light and plug loads circuit, (b) dish washer
(Note: January is highlighted with the black square outline)

CONCLUSIONS

The inverse change-point model technique is used to make the prediction of electricity use in residential buildings in three different climate zones in four locations throughout the U.S, including Louisiana, Texas, Pennsylvania, and Indiana. However, the occurrence of outliers make the inverse models deserves further investigation to understand the underlying causes and occupant-related behaviors. Investigating the reasons why these outliers happened with the highly-granular, 1-minute interval disaggregated electricity data demonstrates that this type of data can be used to determine the particular occupant behaviors that impact residential building energy use. Most of these houses have a wide variation in electricity use of end-uses during the holiday season in winter months. Further study can better characterize these outliers and behaviors across a broad range of homes at a highly detailed level, and is the subject of future work. This will help to determine and characterize specific signatures seen in inverse models, and associate them with specific occupant behaviors.

ACKNOWLEDGMENTS

Electricity use, weather and characteristics of single-family and multi-family houses were collected in coordination with the Pecan Street Research Institute, and Whisker Labs.

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Racking Testing Facility to Evaluate In-Plane Performance of Structural Insulated Panels

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Abstract

There has been a growing interest in learning about the seismic performance of Structural insulated panel (SIP) systems. In particular, an important unknown has been the ductility of SIP systems that is usually governed by panel-to-panel or panel-to-floor/foundation joints behavior. For this primary reason, which is further complicated by the variety of available methods of creating these joints, and the varied use of fasteners, SIPS are not recognized currently by building codes for areas that require designs with sufficient strength, stiffness, ductility and over-strength capacity, e.g., high seismic regions. For SIPS to be adopted by different codes and standards bodies, extensive testing is needed. Limited studies of these systems have been undertaken to compare their performance to conventional-sheathed, wood-framed walls. This paper will discuss a testing facility specially built for light frame testing under racking conditions compliant with and exceeding ASTM E 564 and E 2126 standard test method requirements. The facility permits proper evaluation of components such as SIPs to understand their behavior under in-plane racking conditions that simulate inter-story drift due to earthquakes and strong wind storms. Accurate evaluation of strength, drift and various failure modes in varied SIP configurations with the facility is also discussed.

Introduction

Structural insulated panels (SIPs) are composed of a rigid foam insulation core sandwiched between two structural skins (APA 1990). SIP wall systems provide an economical and effective approach to residential housing (Yeh et al. 2008; Memari et al. 2014). In comparison to conventional wood-framed wall systems, studies of these systems have been limited. Currently, SIPs that are composed of a rigid foam insulation core sandwiched between two structural skins are not recognized by the International Building Code (IBC), the International Residential Code (IRC), or other relevant standards for high seismic regions (Yeh et al. 2008). Acceptance of SIPs into these standards is very important for the SIP industry (FAS 2010). Some wall products, including SIPs, may be recognized for their acceptable seismic performance through the International Code Council Evaluation Service (ICC-ES) acceptance criteria standards (ICC 2009). In some of these standards, evaluation is performed through comparison with recognized systems, such as wood-framed walls.

U.S. building codes do not explicitly cover SIPs for all seismic regions; building officials have the option to approve their use under code-compliance reports, which are typically published by the ICC Evaluation Service (ICC-ES). These reports are based on test data analyses in accordance with ICC-ES AC04, Acceptance Criteria for Sandwich Panels (ICC-ES, 2007). The lack of a consensus-based national product standard for SIPs has affected widespread use of SIPs (Yeh et al. 2008). In an effort to fill the void in the U.S. building codes and to expand the SIPs market, the Structural Insulated Panel Association (SIPA), The Engineered Wood Association (APA), and the National Association of Home Builders Research Center (NAHBRC) jointly developed a prescriptive standard for the design and use of SIP walls in residential construction in 2006 (HUD 2006).

For seismically active regions in particular, unavailability of extensive technical and background information has been one reason why contractors, engineers, and homeowners have not used the SIP products as widely as desired by manufacturers Furthermore, reports of most tests carried out on SIPs are proprietary, and owning SIP manufacturers do not make them available to the general public.

In an effort to advance SIPS to the point where they can be included in the IBC and IRC, additional testing is needed. More mock-up testing of varied wall configurations can inform specialized analyses to derive seismic performance factors for varied SIP wall systems. Such factors are necessary to gain a wider acceptance of these systems in seismic zones.

SIP Basics

SIPs have been used for decades, but their demand has grown significantly since 2000 (Mullens and Arif 2006). SIPs are load-bearing wall elements that are used as an alternative to conventional wood-framed walls (Figure 1). An advantage of SIP construction is that the controlled factory production environment produces a panel of higher dimensional quality (Gagnon and Adams 1999).

The OSB or plywood skins in SIPs act as slender columns and must resist compression and tension, while the core stabilizes the skins and resists buckling (APA 1990). Individual SIPs are joined together in the field with a spline and connection hardware (Figure 2). SIP manufacturers and contractors use various spline designs and different types of connection hardware, which affects the construction procedure and panel strength (Memari et al. 2014). Insulating capability of SIP construction can be engineered by varying foam type and thickness. The most commonly used SIPs in residential construction in the United States consist of a rigid foam insulation core of expanded polystyrene (EPS), and in some cases extruded polystyrene (XPS), polyisocyanurate, or polyurethane, sandwiched between two sheets of either plywood or oriented strand board (OSB).

Figure 1: SIP System (image courtesy of Murus Structural Insulating Panels)

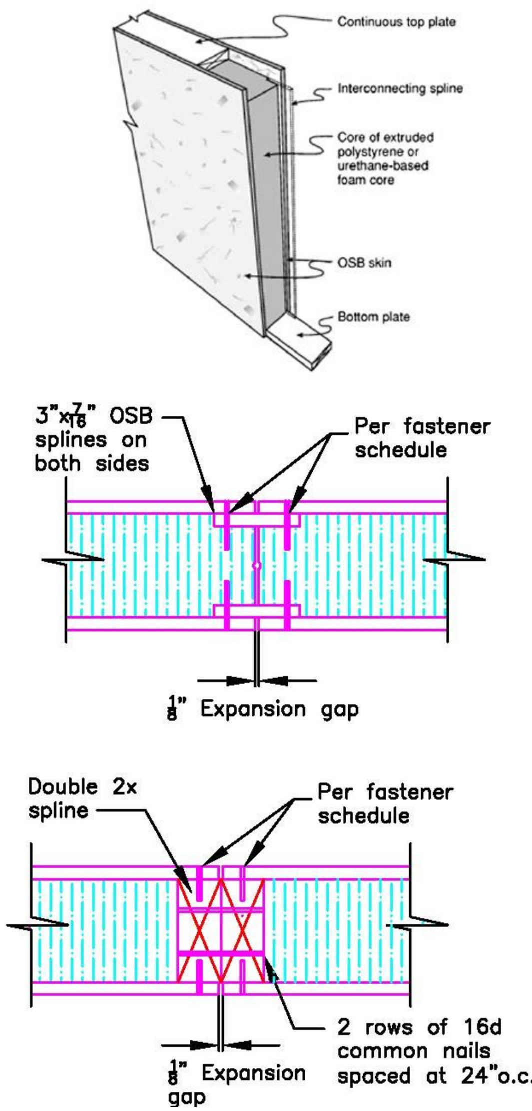


Figure 2: Typical SIP Configuration (image courtesy of Terentiuk 2009)

When the performance of the entire wall system is considered, SIPs perform better than conventional wood framed systems because they are constructed from large, uniformly insulated, airtight components (Memari et al. 2014). With longer SIP lengths there are fewer thermal “shorts” or penetrations in the wall, and the relatively few joints are designed for effective field installation, further reducing air infiltration with respect to conventional wood framed walls (Rudd and Chandra 1994).The panelized nature of SIPs and the use of rigid insulation results in high thermal capacity and reduced construction time. According to Insulspan (2008), a 101.6mm (4in.) thick SIP wall has a uniform R-value of 13.83 compared with a traditional stud wall with fiberglass batt insulation, which only has an overall R-value of 11 (Christian and Kosny 1995).

Jamison (1997) tested several SIP configurations under monotonic and cyclic loadings based on ASTM E564 (ASTM 1995). Mosalam et al. (2008) tested cementitious SIPs (CSIPs) and OSB-faced SIPs under prism shear, monotonic, and cyclic loadings. Terentiuk and Memari (2012) tested 21 SIP panels in accordance with the monotonic ASTM 564-06 (ASTM 2006) protocol, the cyclic CUREE protocol (Krawinkler et al. 2001), and the ASTM 2126-09 (ASTM 2009) protocol. According to the R-Control Tech Bulletin (R-Control Building Systems 2008), 2438.4x2438.4mm (8x8 ft) SIP walls were tested under the Structural Engineering Association of Southern California (SEAOSC) loading protocol (SEAOSC 1996). Terentiuk (2009) also included testing in support of evaluations of other aspects of interest important for seismic evaluation such as fatigue, energy dissipation, and ductility in SIP specimens.

Prior Testing Rig Setups

Experimental studies on SIPs are limited in their comprehensiveness. In 1980 Price and Gromala (1980) evaluated flakeboards in racking test following an ASTM E72 (ASTM 1980) compliant racking load assembly. Their tests used 2438.4x2438.4mm (8x8 ft) wood frames with two anchor bolts securing the bottom of the wood frame to a timber attached to the racking load assembly (Figure 3). Horizontal load was applied at a rate of 5.08mm (0.2 inch) per minute through a timber bolted to the specimen double top plate.

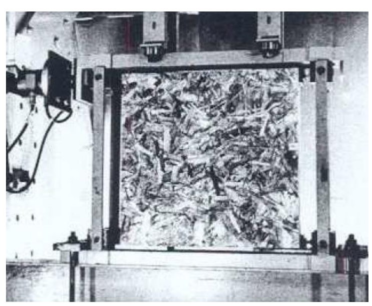
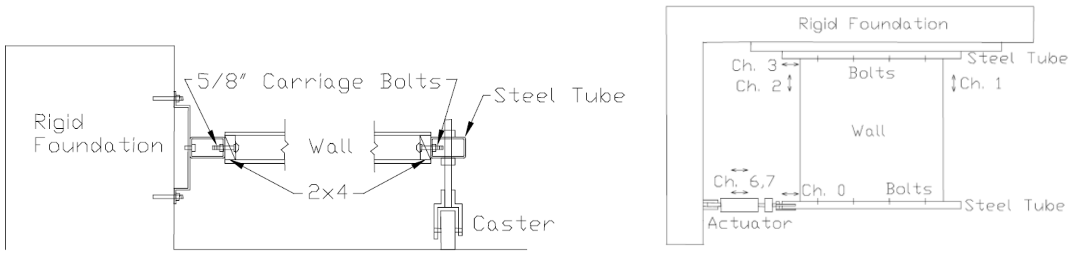


Figure 3: Price and Gromala’s (1980) Racking Load Assembly

Jamison (1997) tested specimens in a horizontal position following the 1995 version of ASTM E564 (ASTM 1995) (Figure 4). This ASTM test set up was preferred over the 1980 ASTM E72 (ASTM 1980) recommendation, since the tie-down rod required per ASTM E 72 setup will effectively resists the overturning moment, so it will not allow the wall anchorage to resist the overturning moment. In Jamison’s work, the testing frame employed a rigid foundation base. A 305 mm (12 in.) stroke hydraulic actuator equipped with load cell and displacement transducer attached to a steel tube applied cyclic movement to the specimen, where such movement was allowed using casters parallel to the loading tube (Figure 4). This arrangement exerted a uniform distribution of the load to the top plate of the wall (Jamison 1997). The displacements on the wall were measured using four LVDT's, while the actuator's force and displacements were measured using a load cell and a displacement transducer.. The data collected from this setup allowed determination of the racking deflection and the rigid-body rotation of the wall (Jamison 1997).



Side View Plan view

Figure 4: Jamison's (1997) Testing Facility

Unlike Jamison's horizontal setup, Mi et al's. (2006) test setup was vertical, where loading to the top plate of the wall was applied through a spreader bar driven by a hydraulic actuator (Figure 5). The bottom plate of the wall was anchored at a spacing of 406 mm to a steel channel secured to the laboratory floor (Mi et al's. 2006). In addition to bottom plate anchors, the end studs were also anchored to the steel channel foundation with hold-downs. To capture data including overall horizontal displacement, slippage between bottom plate and foundation, end stud uplift and shear wall uplift, displacement transducers were used at the four corners (Figure 5).

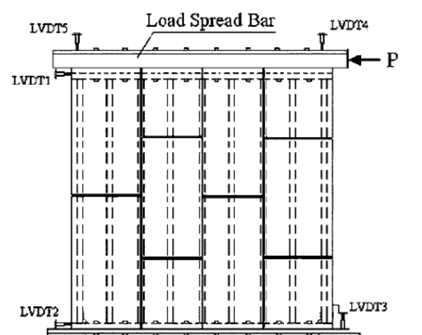
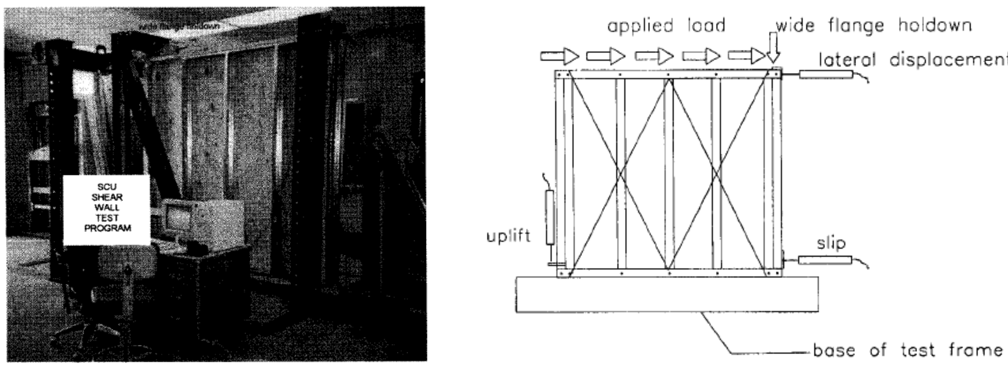


Figure 5: Mi et al's. (2006) Shear Wall Test Facility

Serrette et al. (1997) developed a vertical position test frame for their shear element racking tests (Figure 6). Wall specimens were anchored to the base of the test frame and the overall setup was consistent with the intent of the requirements set forth in ASTM E 72-80 (ASTM 1980). Their facility used a 102 mm (4 in.) stroke manually-controlled, single acting Enerpac RC-504 hydraulic cylinder to apply load along the top track of the wall (Figure 6). Uplift was suppressed by using a wide flange section directly over the load plate, but at the interface of the wide flange and top plate two lubricated 1.6 mm (0.062in) Teflon plates eliminated any friction thus avoiding test-frame in-plane shear resistance. Out-of-plane wall boundaries were configured with angled brackets that provided bracing that eliminated unwanted displacements at the two ends of the wall. Serrette et al. (1997) instrumented their test walls with DC-LVDT displacement transducers at the positions shown in Figure 6. Pump pressure gauge readings were converted to load readings using the effective area of the hydraulic cylinder.



Test Setup Sensor Locations

Figure 6: Serrette et al. (1997) Testing Facility

He et al.'s (1999) used the facility shown in Figure 7 to apply load along the top of shear wall test specimens through a 222 kN servo-hydraulic actuator. In this facility, in-plane reaction frame consisted of a wide flange steel column braced at about mid-height to the floor with two inclined members. Additionally, hollow structural section (HSS) tube bracing stiffened the reaction frame as shown in Figure 7, and out-of-plane supports at each end of the load distribution beam helped maintain in-plane loading as shown schematically in Figure 7. An item unique to this facility, as compared to others discussed, was a static vertical load of 66.7 kN applied using six symmetrically placed hydraulic cylinders connected to the load distribution beam intended to represent occupancy floor loading from two stories above the wall element under test (He et al.'s 1999). Application of displacement-controlled loading through the load distribution beam to the test mock-ups compliant with ASTM E564-76 for monotonic loading and pre-ASTM 2126 cyclic loading protocols was made possible using an Exact-340 function generator coupled to an MTS 458.10 controller.

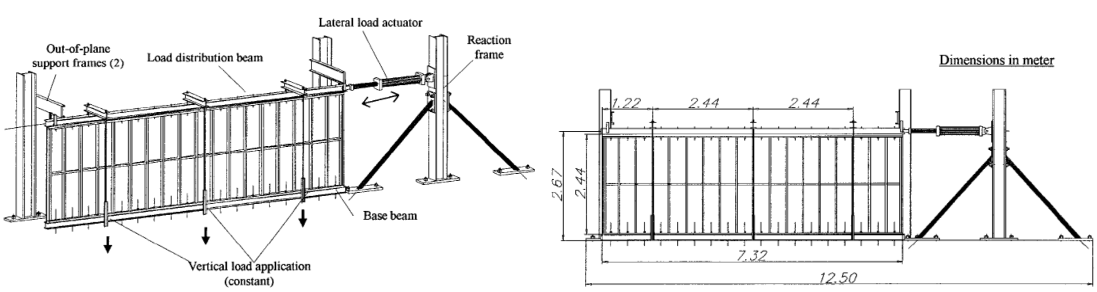


Figure 7: He et al.'s (1999) Shear Wall Test Assembly

Cassidy et al. (2006) conducted testing on full-scale wood shear walls sheathed with FRP-reinforced OSB panels oriented vertically using the facility shown in Figure

8. Displacement-controlled loading of the test mock-ups compliant with ASTM E564-95 were applied for monotonic loading and the CUREE cyclic test protocol (Krawinkler et al. 2001). The shear wall test rig used by Cassidy et al. (2006) employed a 245 kN servo-hydraulic actuator mounted between a reinforced concrete reaction wall and a steel load distribution beam through pin supported connections to minimize rotational and torsional restraint on specimens. The bottom plate of the shear wall test specimen rested on a steel tube base beam bolted to a strong floor. Additionally, the load distribution beam was laterally braced with steel angle members (Cassidy et al. 2006). For this testing frame, DCDTs and string potentiometers were the instruments used to measure horizontal displacements at the top and bottom of the wall and vertical displacements at the bottom corners (Figure 8).

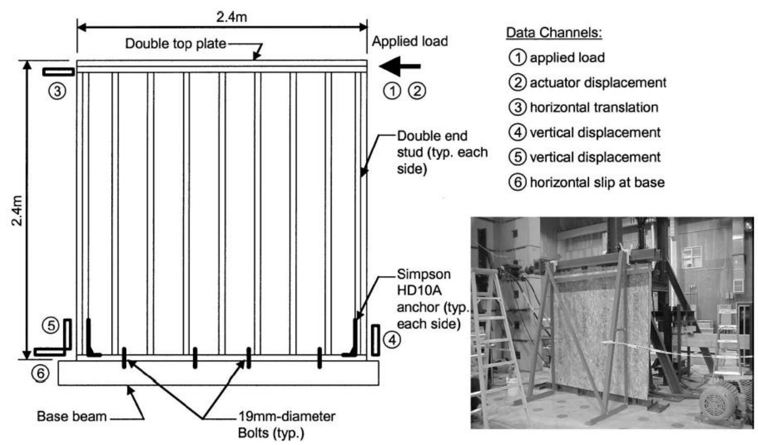


Figure 8: Cassidy et al. (2006) Testing Frame

The Cyclic Racking Facility in The Pennsylvania State University's Building Components and Envelopes Research Laboratory BCERL (Figure 9) was used by Terentiuk (2009) to test SIP wall systems. The test facility employs a 98 kN (22 kip) servo-hydraulic actuator with 152mm (6in.) stroke for full-scale mock-up load application These limits of the test facility were thought to be sufficient considering the maximum loads and displacements employed for similar 2.4 x 2.4-m (8 x 8-ft) SIP walls in previous studies reported by Jamison (1997), Kermani and Hairstans (2006) and in APA Report T2006P-33 (Keith 2006). However, the configurations tested by Terentiuk and Memari (2012) generally exhibited higher ultimate capacities than 89 kN (20 kip). These load and displacement limitations led to the development of a new facility to supplement the Cyclic Racking Facility for SIPs testing.

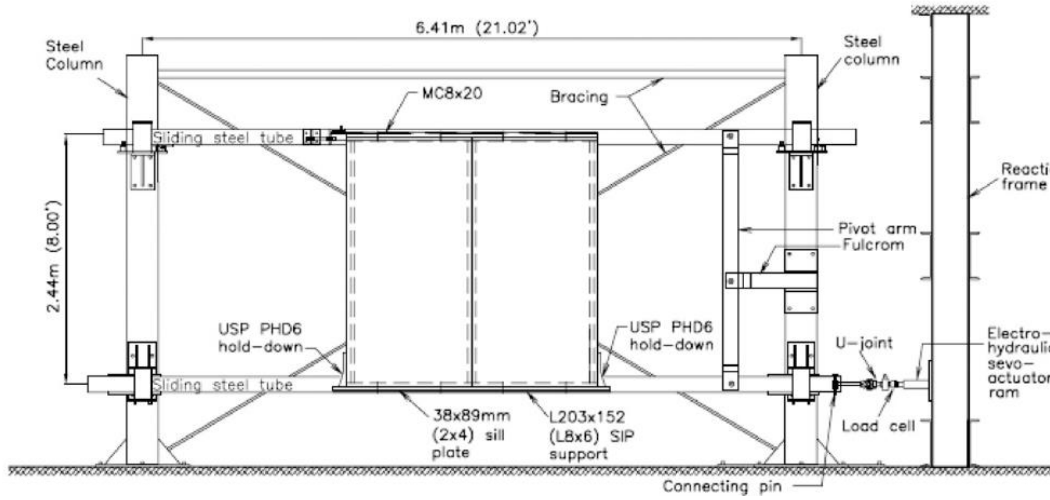


Figure 9: BECRL Cyclic Racking Test Facility

Specimen Testing Sizes and Configurations

When conducting cyclic testing on full-scale SIP mock-ups, the necessary number of tests is dependent on mock-up detailing parameter variations desired (e.g., fastener type and spacing). For compliance with ASTM E2126 (ASTM 2011), a minimum of two tests are needed for each type of specimen configuration, and a third test is needed if the first two tests do not agree (e.g., capacity) within 10%. For statistical purposes, testing of at least three specimens is preferred. Cyclic testing also requires conduct of a static monotonic loading test in accordance with ASTM E564-06 (ASTM 2006) before the cyclic loading test in order to determine target load and displacement values used to define the cyclic loading profile. Thus, four specimens are required for testing each SIP configuration. Typical SIP mock-up sizes are limited by the size of the structural skins, and range from 1.2m x 2.4m (4ft x 8ft) to 2.4m x 7.3m (8ft x 24ft). Panels are joined in the same plane by a spline at each joint. Either one piece of dimensional lumber of the same depth as the foam core or two narrow strips of OSB placed in spline channels immediately below each skin comprise the spline joint.

New LFWLF Testing Facility at Penn State

Overview

BCERL contains a wide assortment of testing facilities ancillary apparatus uniquely fabricated for wall and roof testing to serve the building industry. The multi-disciplinary nature of the BCERL makes it well suited for testing SIPS. For SIP mockup testing compliant with standards such as ASTM E564-06 and ASTM E2126-11 and other research applications, BCERL developed a new testing test facility: the Light Framed Wall Loading Facility (LFWLF) (Figure 10). The LFWLF is capable of testing light framed shear walls and SIP walls for lateral movements and loadings.

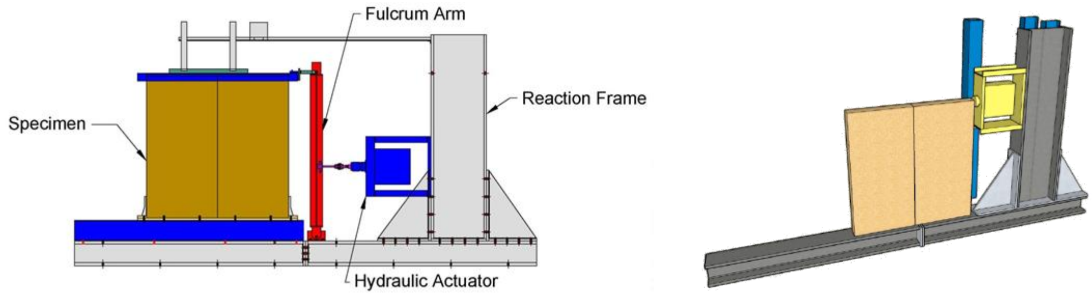


Figure 10: Light Framed Wall Loading Facility (LFWLF)

Setup and System Details

Due to the physical constraints of the BCERL facility, the use of a strong floor and reaction walls, which would be typical for this type of facility, was not possible. The constructed LFWLF uses the basic setup of prior testing facilities that implement a self-reacting frame. Design of the facility went through multiple phases of conceptual layouts, modifications, and adjustments based on the constraints of the facility and testing needs. These constraints, and the decisions made regarding them, were as follows:

- Space designated for the testing facility was relatively limited. Therefore, it was important that the facility be oriented in the vertical direction. This also allows for easier insertion of the testing specimens into the facility.
- The facility will not always be in use, and other BCERL experiments may be conducted in the area during down time. Therefore it was oriented in the space to allow for other equipment and facilities to be used with minimal impact.
- Limitations imposed by the BCERL floor required that the testing facility must also be an independently force balanced (self-reacting) system. That is, any loads applied from the facility upon a testing specimen must also be resisted by the facility alone, and only the gravity load (self-weight) of the facility and specimen is transferred to the floor.
- Negating stabilization attachments, the facility cannot rely on any of the surrounding walls, ceiling, or floor to transfer and resist the applied actuator lateral load and specimen's reaction forces.

Overall the LFWLF is 7.92m (26ft) long and 3.96m (13ft) high as can be seen in Figure 11. The base is constructed of a W14x283 wide flange section. This beam size was selected to provide minimal movement, have adequate width for specimen attachment, and have capacity to resist forces applied to it. The vertical W36x302column was selected to carry potential applied loads while limiting displacement to L/600 during testing. The fulcrum arm in Figure 10 is sized as necessary for the wall mock-up under test and can be fabricated from appropriate W-Shape beams or HSS members. Along the W36x302 are numerous predrilled holes to allow for multiple hydraulic actuator placement configurations.

The test facility uses an MTS Flextest 40 controller coupled to either a 245 kN (55 kip) 254 mm (10 in.) stroke or a 445 kN (100 kip) 152 mm (6 in.) stroke MTS servo-hydraulic actuator to apply monotonic or cyclic profiles under displacement control. The LFWLF uses the fulcrum arm to transmit load, and amplify displacement from the actuator through the arm (loading beam) to the top of the wall specimen. Depending on the location of the actuator relative to the fulcrum pivot points, significantly greater displacements can be achieved with this facility as compared to the Cyclic Racking Test Facility. Figure 12 shows the LFWLF with a specimen loaded and the 445 kN actuator in place. Additional bottom members such as the red base beam shown in Figure 12 can be added to the W14x283 to provide different boundary conditions. The facility around the LFWLF has the ability to configure different lighting and camera arrangements to capture conventional or high speed image streams during testing as needed.

A custom data acquisition system developed for the LFWF uses National Instruments LabVIEW software to acquire real-time sensor data during testing. . The MTS controller and data acquisition system is mounted in an electronics enclosure for protection of these electronic components during testing. Several types of data well beyond the limited requirements in ASTM E564-06 and E2126-11 can be collected during mock-up testing as required for the wall system under test and data needed for the study. This includes:

- Point or full-field strain measurement in mock-ups under test;
- Strain in mock-up components such as connectors/attachments;
- Rotation of SIPS;
- Deflection of SIPS parallel and perpendicular to the applied load
- Deflections in the facility or in specific areas of the mock-up;
- Load applied to the specimens or load distribution within the mock-up;
- Environmental parameters for enhanced testing (e.g., ambient condition variations)

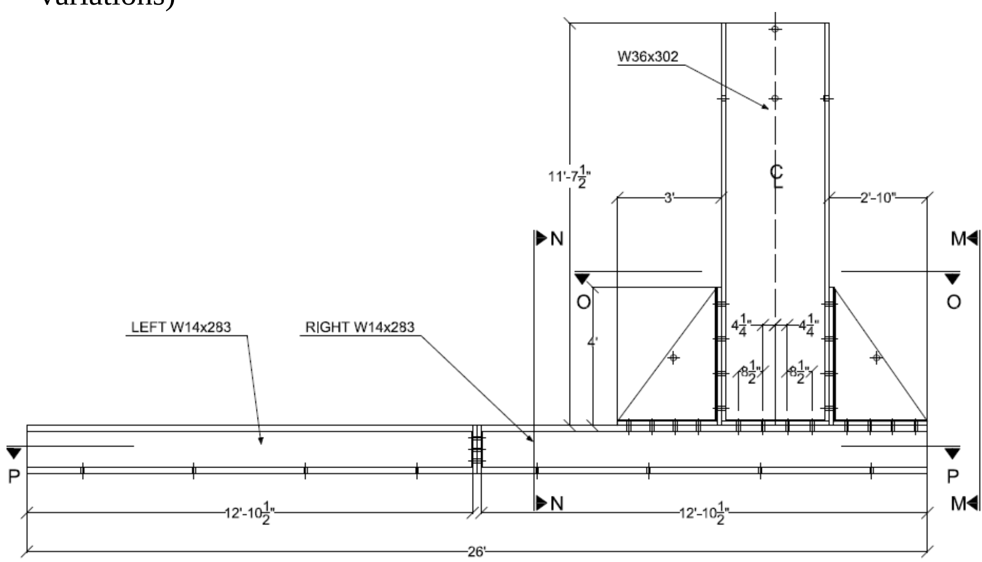


Figure 11: LFWLF dimensional constraints.

Figure 12: LFWLF with mock-up before being tested.

A typical data acquisition (DAQ) system configuration uses a collection of twenty displacement, rotation and load sensors selected from the array of available sensors in the BCERL to provide detailed information about various aspects of the wall system's behavior. The DAQ system is modular; e.g., if strain gages are required, National Instruments (NI) SCXI 1314 front mounting (8-channel) terminal blocks that plug into an NI SCXI 1520 Input Module can be used. For deflection measurements, DC linear variable differential transformers (LVDTs) or string potentiometers are typically deployed. Linear slides are used as necessary to prevent transmission of loads into the LVDT displacement sensors. Rotation sensors mounted to a custom xy linear slide arrangement are often used for panel and fulcrum arm rotation measurements. Lucas Schaevitz DC-EC-1000 LVDTs with a range of 50 mm (2 in.) with an accuracy of 0.025 mm (0.001 in.) are often used. Displacement sensor range and mounting arrangements are selected to accommodate flexible/deformable specimens. Figure 13 shows where the 13 sensors would be placed for a typical two-panel SIP configuration mock-up test. Actuator displacement is measured using the actuator's internal displacement sensor not shown, and a fatigue-rated load cell is used to measure the load applied by the actuator.

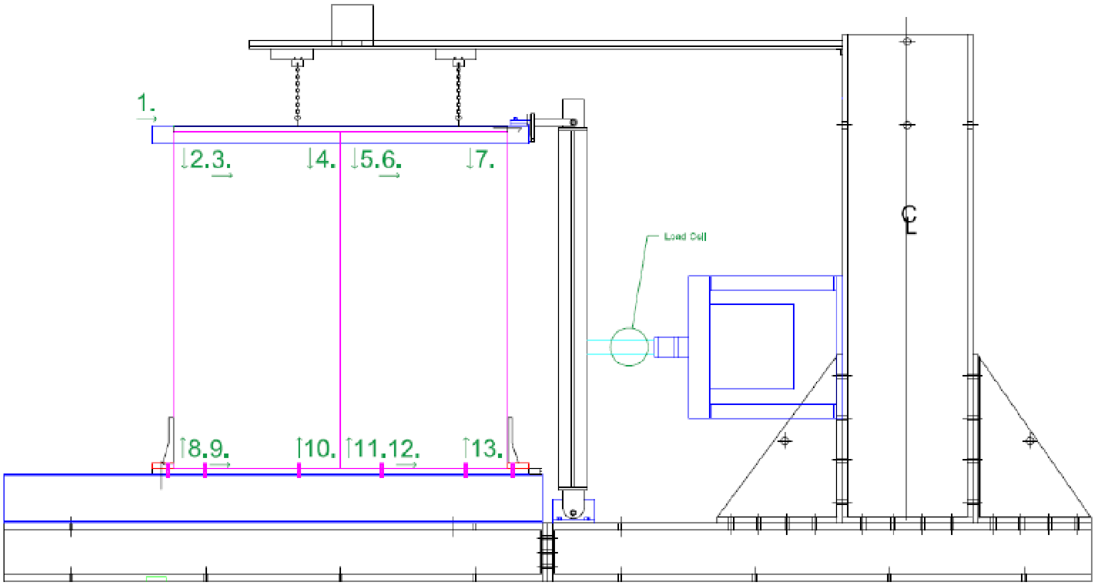


Figure 13: Typical sensor locations for a two panel SIP mock-up

BCERL Capabilities

The LFWLF can accommodate mock-ups with maximum dimensions of 3.96m (13ft) wide and 3.66m (12ft) high (Figure 11). The 3.96m (13ft) width permits for example up to 3-4 SIPs jointed together or jointing of two 1.22m (4 ft) panels to form a mock-up for testing. The 3.66m (12ft) height limit allows 3.66m (12ft) long panels (oriented vertically) to be tested, but testing taller panels is not possible due to ceiling height limitations in the BCERL. Parametric variations of mock-up configuration parameters such as spline design, connection hardware, hold-down methods, and bearing of the sheathing on the top and bottom plates are necessary for inclusion in full-scale testing investigations to determine their effect on the SIP wall system performance. The LFWLF permits these configuration variables to be changed and tested with relative ease.

Wall specimens are fixed to the facility base using anchors and other mounting means used in actual practice for the wall system under investigation to ensure that the wall system boundary conditions are realistic. ASTM E72 (ASTM 2015) prescribes the use of tie-rods as the hold-down mechanism to simulate boundary conditions, while ASTM E564-06 (ASTM 2012) uses devices or connectors that attach the frame bottom to the supporting base. The rationale for using tie-rods is to eliminate uplift in order to evaluate the shear capacity of the sheathing material for any given nail or screw spacing. ASTM E72's usage of tie-rods is clear and unique while ASTM E564-06 is non-specific, and may lead to the use of different hold-down devices, which must be communicated in test reports.

Two primary types of loads need to be considered for lateral performance of SIPs: static monotonic loading and cyclic loading. Both methods of loading are used to test wood-frame shear walls. As noted, the LFWLF is designed for application of these types of loading protocols for any wall mock-up that fits within the dimensional limitations and loading capacity of the facility. The loading protocol can be static, as prescribed in the ASTM E564 standard, or cyclic, as prescribed in ASTM E2126 (ASTM 2011), which is of interest mainly for evaluating seismic resistance.

Monotonic testing procedures have long been standardized as ASTM E72 (ASTM 2015) and ASTM E564 (ASTM 2012). ASTM E564 is followed to determine the load-displacement relationship of the wall system under test. The loading protocol requires that the load be applied directly to the top plate of the wall.

As described in the literature review presented, cyclic loading protocols have been evolving to create realistic seismic loading conditions for laboratory testing. The loading rate is small enough to consider these protocols as "static" or "quasi-static", while having complete reversal of load in a cyclic manner. Cyclic loading protocols that have found wide application over the years in laboratory testing include:

- Sequential Phased Displacement Protocol (SEAOSC-SPD)
- ASTM E2126 "Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Walls for Buildings"
- Consortium of Universities for Research in Earthquake Engineering (CUREE)

The various protocols differ in several aspects including the number of required cycles of increasing amplitudes to reach a certain amplitude for constant amplitude cycling (if any), number of cycles during the constant amplitude interval, number of cycles for the amplitude decay interval, target maximum amplitude, and loading rate. In general, these protocols rely on a target displacement, which is defined as the yield displacement. The CUREE-Caltech wood-frame project is the preferred protocol for SIP testing because the number of cycles are fewer and are more consistent with what is expected in real California design earthquakes. Furthermore, the potential for cumulative damage in the wood frame has been considered.

The CUREE protocol uses an estimated target displacement obtained from a monotonic test to determine the amplitudes of the cyclic loading. From the monotonic loading test, the load at 80% of peak load on the descending curve (degradation) and its corresponding displacement is used to set the cyclic loading protocol. 60% of this displacement is assumed to be the drift that corresponds to the peak load and is the reference displacement for the cyclic loading protocol.

Concluding Remarks

Advancing structural engineering knowledge of how SIPs perform under static and dynamic interactions requires a facility like the LFWLF. The facility is highly versatile for structural testing of SIPs. Structural engineers and architects need to have a better understanding of the effects of fastener size and fastener spacing as design variables to advance the SIP industry within residential applications. SIP configurations possible with the LFWLF include:

- Different size panels (width and height) and varied aspect ratios;
- Different size and spacing of openings;
- Brick veneers and other exterior wall coverings attached to SIPs;
- Varying spline connector design;

- Connection hardware for SIP-to-SIP connections and SIP-to-other structural elements;
- Bearing of sheathing on the top and bottom plates.

Because SIPs are either not addressed or addressed in a limited manner through prescriptive measures in the 2012 Wood Frame Construction Manual (AWC 2012), 2015 Special Provisions in the Design for Wind and Seismic (SPDWS) (AWC 2015), or 2015 IBC and IRC (ICC 2015a and 2015b), this leaves designers with a dilemma when designing structures that have SIP-based systems, particularly in seismic controlling areas. To partially address this, studies sponsored and or supported by the USDA Forest Products Laboratory and the Structural Insulated Panel Association (SIPA) have been undertaken (HIRL 2013). Much more work still needs to be done in order to have SIPs added to these Building Codes and Standards for all actual seismic areas.

Acknowledgments

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Experimental and Numerical Study of Moisture Movement in Sealed Attics

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ABSTRACT

Leaky ductwork in vented attics account for about 25% of energy lost in single-family residential houses per year. One way to conserve energy is to seal the underside of the wood roof sheathing and the attic vents with spray applied polyurethane foam insulation. However, in hot sealed attics, the humidity levels can reach saturating levels creating favorable conditions for moisture to condense at the underside of the sheathing. Moisture in wood should be controlled within 20% to prevent moisture related issues. This paper describes a combined experimental and numerical study of moisture and heat movement in code compliant residential houses with sealed attics in Florida. The time histories of temperature, relative humidity and moisture in the conditioned space and the attics were measured for a 12-month period in four Florida houses. The air leakage areas and salient house characteristics were recorded for use in numerical modelling. Poor workmanship in sealing the attic causes high attic air leakage resulting in poor indoor thermal comfort. The field-measurements showed less potential for condensation in all four houses and the moisture contents in wood remained well below the 20% threshold for mold formation. A numerical tool was developed to simulate the moisture movement by varying air leakage rates and occupancy habits to predict the moisture content in the wood sheathing. The results of the numerical modelling were calibrated against field-measurements; and showed good prediction accuracy. Future scope exists for the improvement of the numerical tool by accurately modelling the air change rate in the house and the attic.

INTRODUCTION

This paper presents the methods and results of a combined experimental and numerical study of moisture movement in Florida residential houses with sealed attics. Traditional residential house attics have vents in the soffit, ridge and the gable ends.

The air exchange occurring through the vents removes the excessive moisture in the attic. The vents also allow conditioned air leaking from the ductwork in the attic to move to the outdoor environment. Duct leakage in vented attics is a major source of residential energy losses as the construction industry strives to make houses sustainable. To control the duct leakage, a new construction technique was put forth that encapsulates the attic and the ducts within the thermal envelope by spraying polyurethane foam insulation under the wood roof sheathing. The attic vents become obsolete to minimize the interaction with the outdoor environment and the sealed attics have a climate more synonymous to the indoor conditioned space.

Wood is a hygroscopic material and its properties alter with changes in the moisture content. Moisture content below 20% is considered optimum for construction and structural purposes. Bergman (2010) states that mold and mildew forms as moisture crosses above 20% and the structural capacity lowers when the moisture reaches more than 30%. In vented attics, the continuous air movement removes excessive moisture and inhibits any condensation over the wood sheathing. In sealed attics or unvented attics, the air movement is restrained and cool wood sheathing in winter provides favorable conditions for moisture laden indoor air to condense. Several studies performed on sealed attics in humid climates by Lstiburek (2015) and Miller et al. (2016) suggest that condensation can at the sheathing-to-insulation interface. The condensation being undetected due to the underlying insulation layer might cause deterioration in structural capacities over prolonged moisture condensation as shown in Figure 1.

Figure 1. Visible mold in vented attics. Unvented attics inhibit visible warnings

Miller et al. (2013) measured the heat and moisture flow in an unoccupied research house with different roof configurations. The control attic had an R-38 insulation layer at the ceiling level. Two sealed attics with R-22 ocSPF and R-22 ccSPF under the roof deck were analyzed in the study. The vented attics had less than 60% relative humidity during the day time for seven contiguous days in summer. However, the sealed attics had 100% relative humidity on two of the measured seven days during the day time. The relative humidity had an inverse trend to that of a vented attic and remained above 60% throughout the seven days. The weekly trend in relative humidity is shown in Figure 2.

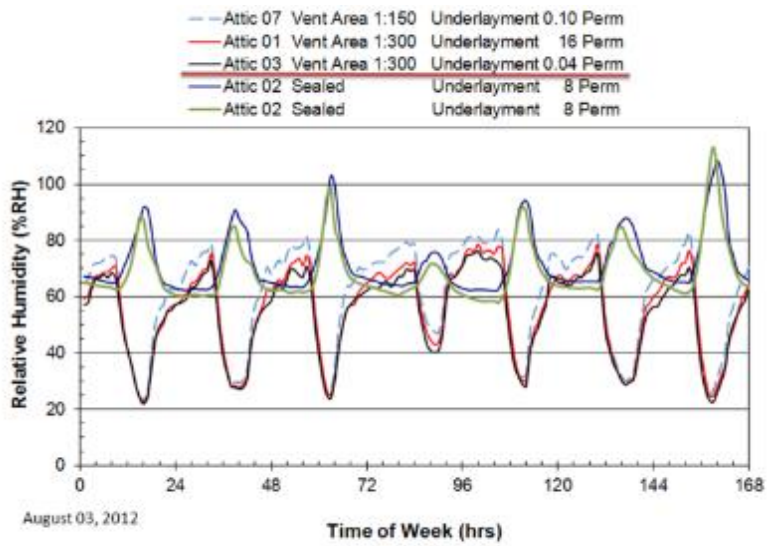

Figure 2. Sealed attics have saturating levels of relative humidity during solar noon. Vented attics have less than 80% relative humidity

Building code requirements for sealed and unvented attics

Table 1 shows the insulation requirements defined in the Florida Building Code. Insulation R-value represents the thermal insulating capacity of a material. The higher the R-value, the higher is its insulating capacity. Open-cell spray polyurethane foam is an air permeable insulation and did not have any prescription or performance requirements prior to 2014 in the Florida Building Code. In the 2014 version of the Florida Building Code, an R-5 rigid insulation layer is required above deck when air permeable (spray foam) insulation is directly applied under the roof deck for condensation control. (Section R806.5) Builders typically try to achieve either the R-19 or the R-30 insulation requirements, by applying spray foam to the underside of the roof deck, either 5 in. thick or 7 in. thick layers respectively of ocSPF.

Table 1. Florida Building Code requirements for thermal insulation

Florida Building Code	Attic Floor Prescriptive Requirement		Attic Floor Performance Requirement		Sealed Attic Requirement	
Year	CZ-1	CZ-2	CZ-1	CZ-2	CZ-1	CZ-2
2001 – 2012	R-30	R-38	R-19	R-19	NA	NA
2014	R-30	R-38	R-19	R-19	R-5	R-5[1]
[1] R-5 prescribed only for closed-cell insulation and not open-cell insulation						

EXPERIMENTAL ANALYSIS

To test the moisture durability of code compliant sealed attics, the Florida Building Commission (FBC) contracted researchers from the University of Florida (UF) and the Oak Ridge National Laboratory (ORNL). The research team tested the behavior of sealed attic systems in the field with respect to occupancy in four single-family residential houses in Florida. The Florida Roofing and Sheet Metal Contractors Association (FRSA) assisted in finding house owners interested in the research. Prevatt et al. (2016) conducted preliminary surveys and identified house characteristics like number of occupants, type of roof cover and sheathing, type and thickness of insulation for eight houses with sealed attics. From surveyed houses, four houses with open-cell spray polyurethane foam insulation in the attic were selected for the field test. All house owners were involved directly or closely with the construction industry, hence all selected houses had excellent roofing and no problems associated with rain water intrusion.

The four selected homes are located in West Palm Beach, Venice, Orlando and Gainesville. Further in this paper, the houses will be referred to as House 1, House 2, House 3 and House 4. House 1 in Palm Beach county borders the ASHRAE defined climate zones 1A & 2A; other three houses fall within climate zone 2A. Retired couples are the house owners for all four houses. House 4 is a retirement home occupied only during the winter period. The front view of the selected research houses is shown in Figure 3.

Figure 3. Front view of selected field houses

Air leakage testing was performed at the research houses to quantify the building envelope and duct air leakages. The amount of air leakage can affect the heat and moisture movement as well as the indoor thermal comfort of a residential house. The blower door and guarded blower door results show that the retrofitted sealed attic (House 1) has the highest attic air leakage. This is a direct result of poor workmanship of sealing the attic. As a result of the poor workmanship, more heat flow occurs into the conditioned space of the house. The duct blaster test results show that House 1 has well sealed duct system. For House 3 and House 4, the guarded duct blaster test could not be performed due to lack of equipment.

The indoor thermal comfort of occupants is determined by the temperature and humidity inside the house. The optimum comfort conditions are defined in ASHRAE Standard 55 (turquoise shaded area in Figure 4). House 1 has the least indoor thermal comfort owing to the higher attic leakage. The air leaking from the outside to the attic cannot be controlled by the 4.5 in. thick insulation layer at the roof level.

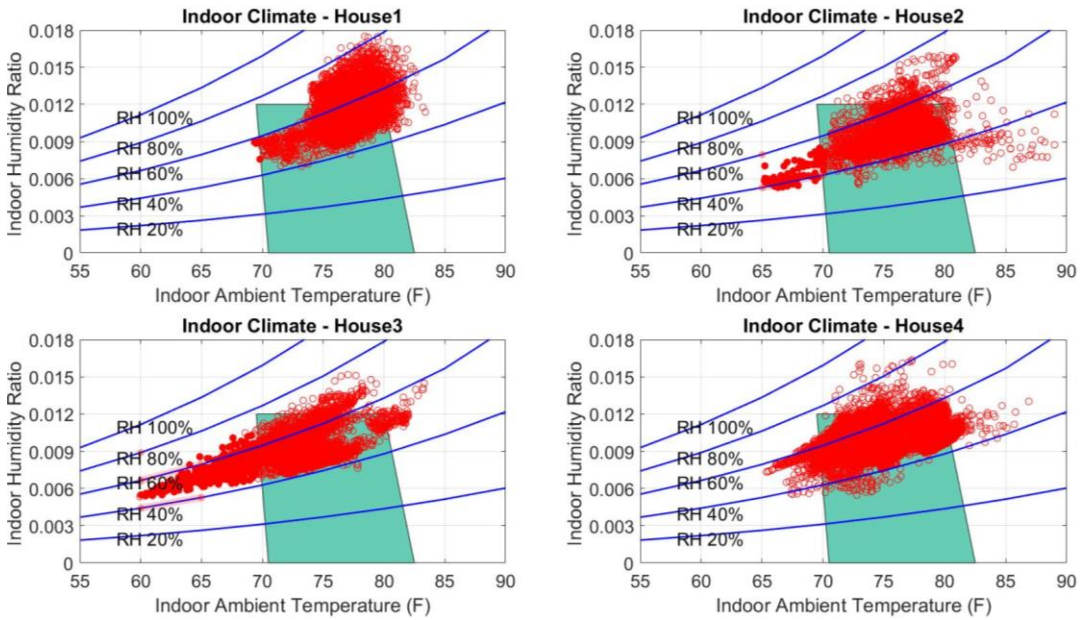

Figure 4. Indoor thermal comfort compared to ASHRAE Standard 55

Heat and Moisture Movement in Sealed Attics

To identify the potential for condensation at the roof sheathing-to-insulation interface, it is important to understand the movement of heat and moisture in a sealed attic. The primary sources of moisture in the attic arises from occupant habits, rain water intrusion, and water vapor diffusion due to vapor pressure drive. The houses selected for the research are well constructed with code compliance, inhibiting the passage of rain water (liquid water) into the roof system. To test the moisture durability of the roof section, temperature, humidity and moisture sensors were installed at the sheathing-to-insulation interface and the data was collected for a contiguous 12-month period. The orientation of the installed sensors is shown in Figure 5.

Data is measured every 30-seconds and is reduced as raw data averages over 15-minute, 60-minute, and 24-hour intervals. Post processing of the raw data yields weekly or annual records containing data averages over 15-minute and 60-minute intervals for all four houses. 60-minute averaged data is analyzed in this paper. The sensors were placed in the same pattern for each home to provide consistent comparisons among the attics under field study. Absolute humidity probes were installed for measuring the outdoor, the indoor and the attic ambient temperature and relative humidity. Absolute probes were also placed on the underside of the roof sheathing about mid-span from eave to ridge. An absolute probe was also placed on the sheathing at the north-side of the roof ridge. The probes met the manufactures specification for the temperature response of +/- 0.2°C. Humidity sensors were checked at 25, 50, 75 and 90 % RH. The error in RH ranged from 2% of reading at 25% RH and 15°C to 6.5% of reading at 90% RH and 26°C.

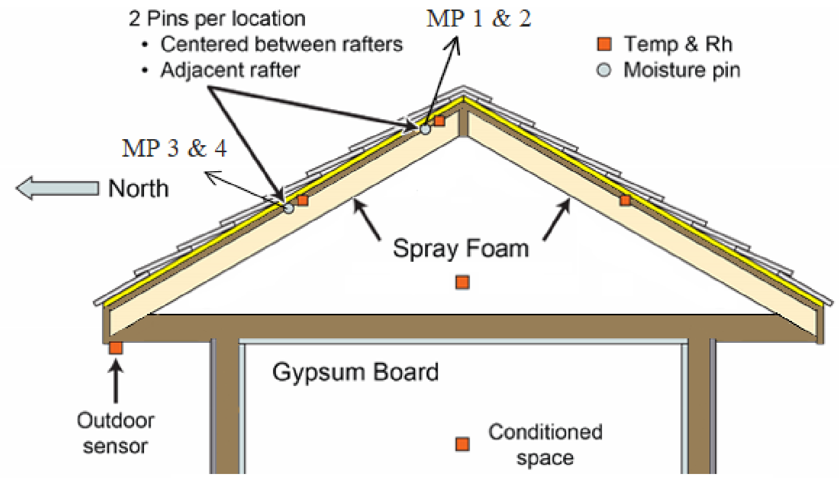

Figure 5. Orientation of temperature, humidity and moisture sensors

The four Florida houses had humidity levels constantly over 65%. Most sealed attic constructions have no insulation at the ceiling level. The roof area is larger than the ceiling level and the triangular roof shape provides a challenge in obtaining the required thickness of the spray foam. If the insulation levels are lesser than code levels, more heat flux would occur into the conditioned space making the HVAC system run longer. Hence necessary care should be taken in spraying code levels of insulation under the roof sheathing. High humidity inside the attic creates a vapor pressure differential that drives the attic moisture through the spray foam and onto the underside of the wood sheathing, which serves as the first condensing surface during cold outdoor conditions.

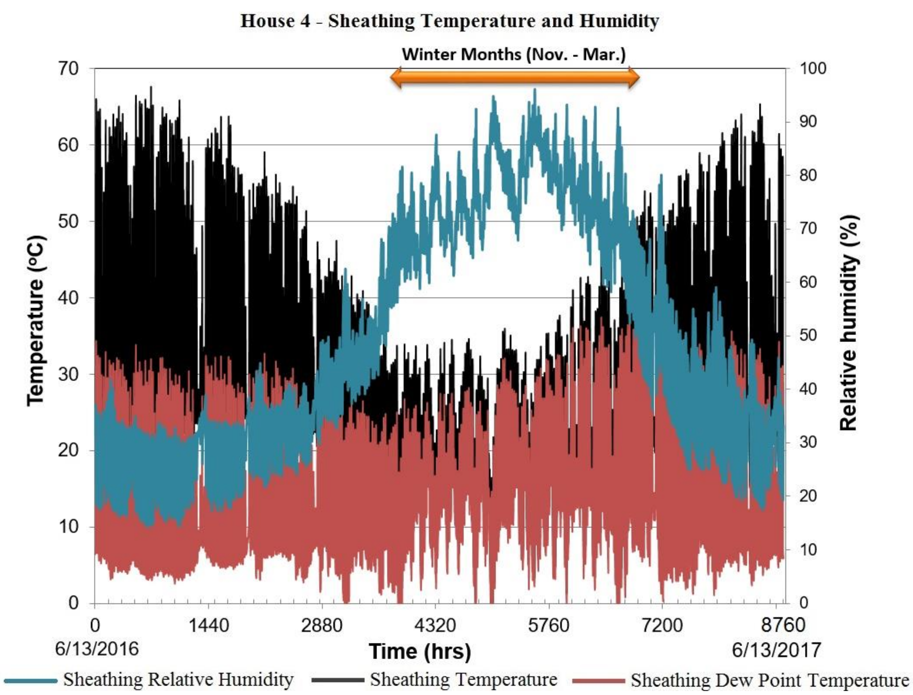

Figure 6. Roof sheathing temperature and relative humidity for House 4 in Gainesville

The homeowner of House 4 in Gainesville occupies the house only during the winter period and sets the thermostat to 80°F during the summer months. The thermostat setting causes high humidity ranges over 80% and near saturation levels in the sealed attic. Salonvaara et al. (2013) had analyzed sealed attics with open-cell polyurethane foam insulation in Florida and observed that humidity ranges over 80% in the attic caused moisture accumulation in the sheathing-to-insulation interface. This effect of higher attic humidity causing risk of moisture accumulation is analyzed in this study. The sheathing temperature, humidity and dew point temperature are plotted in Figure 7.

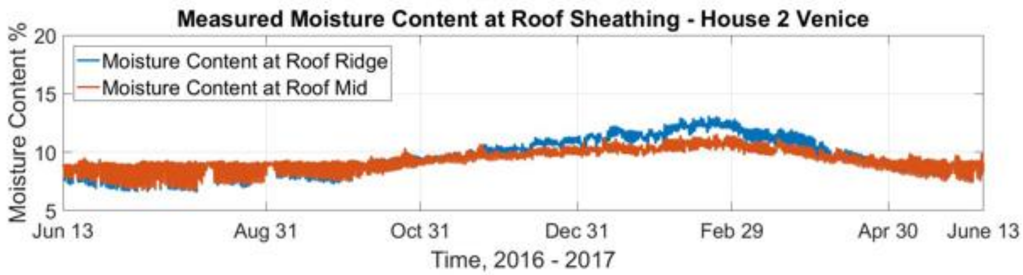

Figure 7. Roof sheathing moisture content (%) for House 2 in Venice

For House 2 in Venice, the moisture content in the ridge was higher than the moisture content in the midpoint during the winter period (Figure 7). This could be explained because of the excellent workmanship in House 2. When an attic is well sealed with spray foam insulation and there is no possible source for rain water shedding, the moisture in the roof sheathing is driven by water vapor diffusion and pressure differential between the outside environment and the attic. The buoyancy of the saturated water molecules tends to shift the moisture upwards towards the ridge of the moisture content. This effect is explained in a clear manner in Lstiburek (2016).

The sheathing temperatures in House 4 reach the dew point temperatures during the winter months of November to March. The sheathing relative humidity is above 80% and reaches over 95% for a short time, especially around January months. This period of two weeks show the highest moisture content in the roof sheathing, with the moisture levels reaching up to 20% as shown in Figure 8. This behavior confirms the relationship posed by Boardman et al. (2017). However, the effect has to be analyzed further to understand this anomaly in the moisture content values. This could be due to occupant activity since the house is typically occupied only during the winter period. However, the moisture contents reached a safer level during the first week of February 2017.

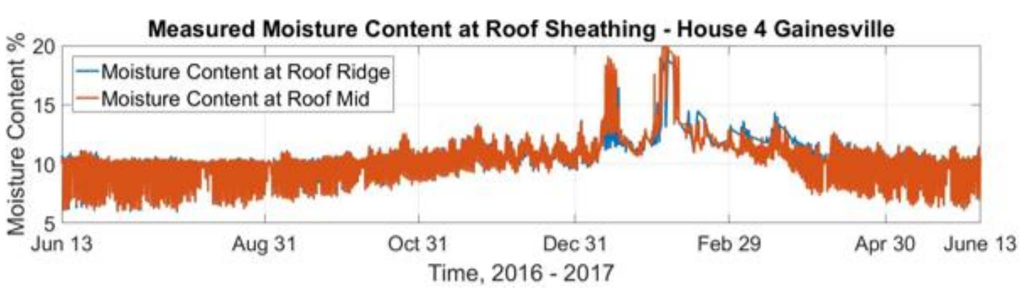

Figure 8. Roof sheathing moisture content (%) for House 4 in Gainesville

Hurricane Matthew and its effects on House 1

In early October 2016, Hurricane Matthew tracked along the eastern seaboard of Florida. House 1, situated in West Palm Beach was the closest to the path of the hurricane. The measured data is used to visualize the hygrothermal behavior of the attic during the hurricane. Cloud cover and precipitation (Figure 9) caused the sheathing's temperature to drop about 15°C below temperature levels shown for three consecutive and earlier days. In addition, the relative humidity measured in the attic does not show the same trends observed for the three earlier days seeing clearer sky.

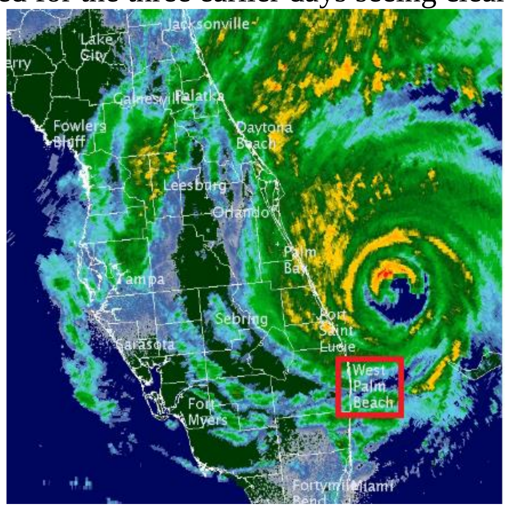

Figure 9. Hurricane Matthew tracking along the east coast of Florida. Source: National Weather Service

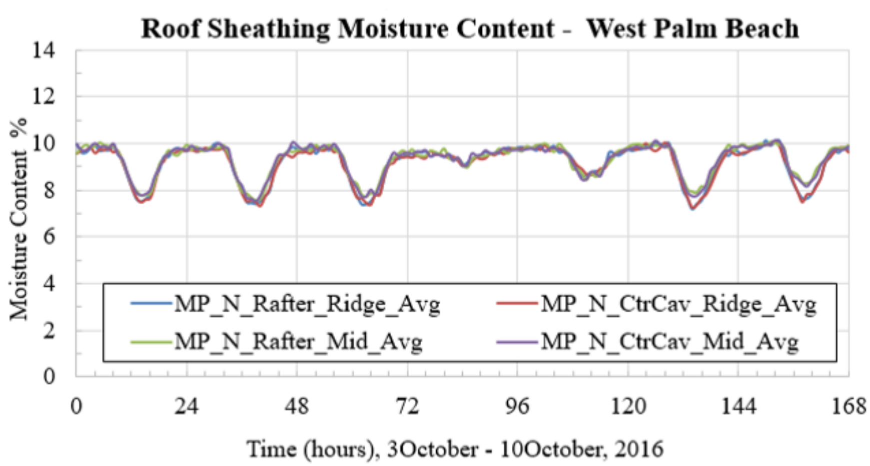

Figure 10. Roof sheathing moisture content for House 1 during hurricane

The diurnal variation of the moisture content of the roof sheathing also differed from that observed for the three earlier days. Cloud cover shaded the roof during the storm, the roof was wet from precipitation but the moisture content did not raise or drop during the afternoon hours as observed for the three earlier days of data. The differences in trends are due to the presence (3 days prior to storm) and absence (during storm) of solar radiation. (Figure 10)

The above observation led to the conclusion that the moisture in the attic originates primarily from inside the house, due to occupant activities but can also emanate from air leakage crossing the outdoor to attic boundary. During evening hours, the night-sky radiation cools the roof deck below the outdoor ambient temperature and unwanted moisture in the attic diffuses by the gradient in vapor pressure through the spray foam and enters the wood sheathing. Hence, the moisture content in the wood deck is higher at night. During daytime, the solar radiation drives the moisture from the wood sheathing back into the attic air, which causes a rise in attic relative humidity. The sheathing's moisture content drops around solar noon and the attic humidity reaches peak values. The effect of the solar driven moisture diffusion was clearly documented during sunny days and the phenomenon was absent during rainy days or when thick cloud cover blocked the irradiance. The weather effect of Hurricane Matthew on House 1 caused less moisture from the sheathing to be driven into the attic air as compared to days having solar irradiance bearing down on the roof.

NUMERICAL ANALYSIS – PROBABILISTIC RISK ASSESSMENT TOOL

The Probabilistic Risk Assessment Toolkit (PRAT) is a probabilistic indoor climate and sheathing moisture content assessment toolkit. This toolkit utilizes three software packages – Building Energy Optimization (BEopt), Energy Plus (ENERGY PLUS) and WUFI 1D. ENERGY PLUS is a whole-building computer tool developed by the Department of Energy (DOE) focused on modelling the energy consumption in residential and commercial structures by simulating interzonal air and moisture flow along with temperature and humidity conditions. BEopt is used as a front-end graphical use interface (GUI) for Energy Plus. WUFI is a hygrothermal modelling software used to analyze the heat and moisture movement through building materials.

Table 2. Input data for the PRAT numerical tool

Building Energy Optimization BEopt	Energy Plus	WUFI 1D
• House location and climate throughout the research period • House geometry and material properties • Building occupancy conditions • Measured thermostat temperatures • HVAC schedules • Effective Leakage Areas (ELA) for leakages from attic to outside, living space to outside, living space to attic.	• Attic duct leakage • Interior moisture generation rate • Interior heat generation • Thermostat set points	• Roof section details • Air leakage rates from ENERGY PLUS • Outdoor Climate

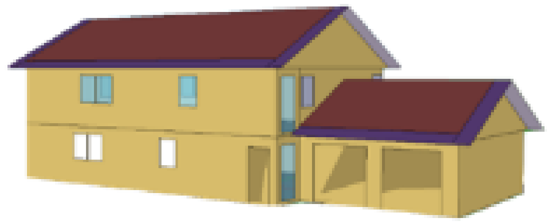

Figure 11. Generic house model used for numerical simulations

For the numerical analysis, several inputs were used as elaborated in Table 2. A generic house model (Figure 11) used for the analysis has a two-story hip roof with asphalt shingle cover and a plan area of 2400 sq.ft. 10in. of open-cell spray polyurethane foam insulation is applied under the roof sheathing as the thermal insulation. Two stages of numerical analysis are performed to test the accuracy in prediction. For the first stage, the generic house model is used along with probabilistically varied inputs. The inputs are varied stochastically to represent the conditions present in a typical single-family residential structure with two occupants. The resulting attic temperature, relative humidity and moisture content are calibrated against the field-measured data. For the occupancy conditions specified in Energy Plus 1000 variations of attic temperature for a generic house is shown in Figure 12.

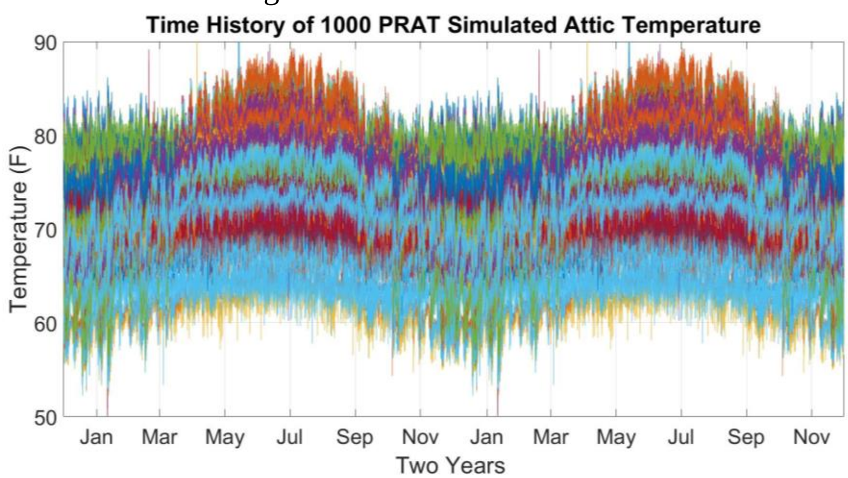

Figure 12. 1000 variations of PRAT simulated attic air temperature

The PRAT simulated attic temperature and relative humidity should be calibrated against the field measured data for evaluating the accuracy in the prediction capacity of the PRAT. Visual comparison of the two datasets confirm the spread and variability while statistical comparison is presented to establish the accuracy and bias in prediction. Figure 13 and 14 present the initial comparison of the attic temperature, relative humidity and roof sheathing moisture content. The results are presented for House 2 and House 4.

House 1 had extreme attic air leakage and behaved like a vented attic. House 3 did not have any ductwork in the attics; House 2 and House 4 were selected for the numerical analysis of heat and moisture movement in sealed attics.

The initial six-month comparison between field-measured and simulated data show that the simulated data forms a large band due to large variations in the input parameters. The measured attic temperature falls near the upper bands of the simulated data and the relative humidity falls near lower bands of the simulated data as shown below.

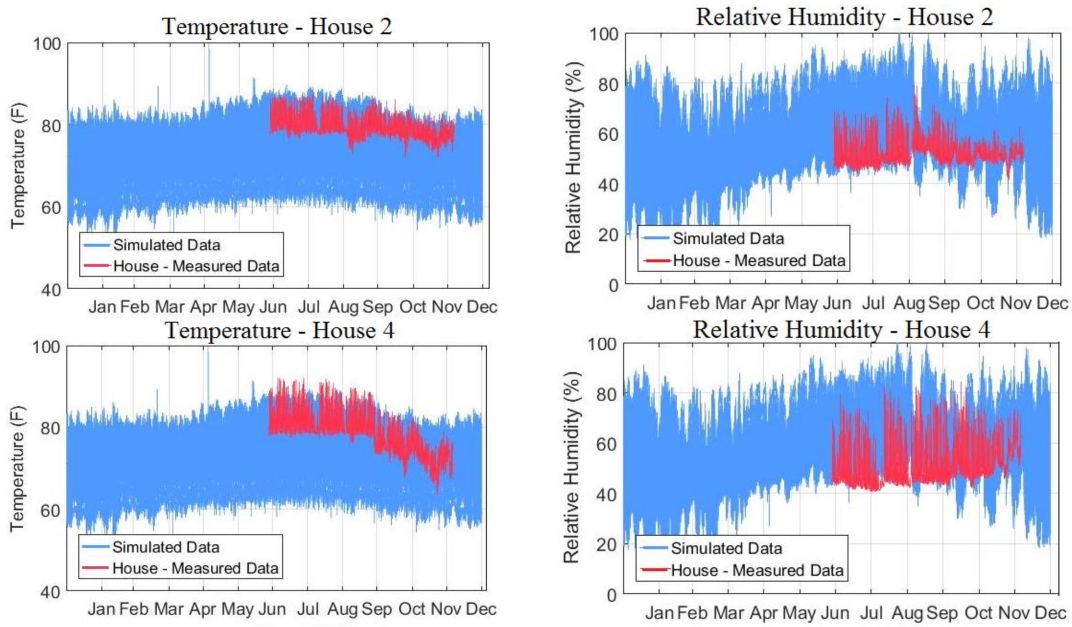

Figure 13. Comparison of PRAT simulated and field-measured data

The PRAT simulated roof sheathing moisture content for a generic house model is shown below in Figure 14. The 1000 variations in the simulations are fairly similar and superimpose over each other at several time periods indicated by the blue color. The moisture contents are well below the 20% risk threshold due to moisture induced problems.

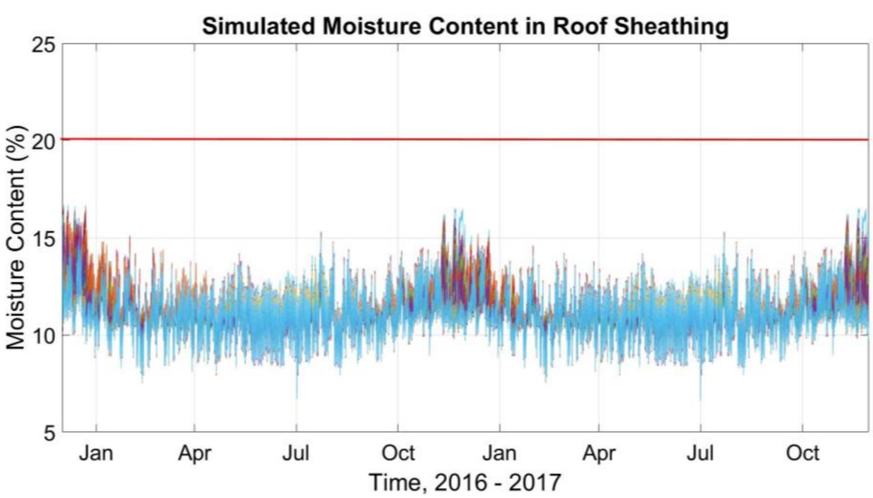

Figure 14. 1000 variations of PRAT simulated roof sheathing moisture contents

The generic house model with probabilistic inputs has a large bandwidth and cannot accurately represent the field measurements. The inputs need to be fine-tuned to simulate conditions matching the field. Hence, several revisions were made to the input data by using field-measured air leakage and duct leakage. The thermostat temperatures were set to replicate the usage in the houses. The indoor heat and moisture (latent and sensible heat) conditions produced due to occupant habits such as bathing, cooking, HVAC usage were mirrored by using data from the Lawrence Berkeley National Laboratory database of residential energy usage and the Residential Energy Conservation Survey database.

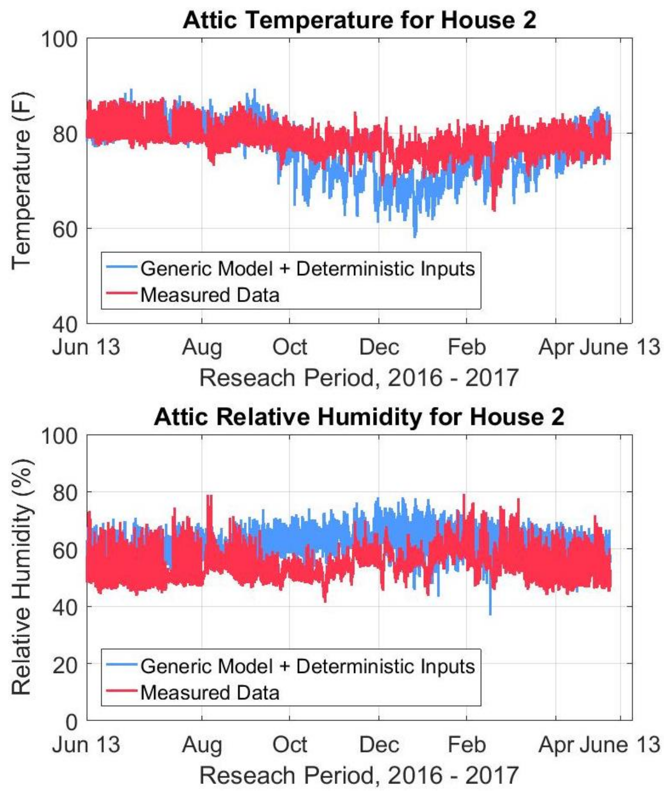

Figure 15. Attic temperature and relative humidity – PRAT vs measured

The PRAT simulated attic temperature and relative humidity from the second stage of numerical analysis closely followed the field-measured values during the summer months. The PRAT captured the field conditions better for House 2 than House 4. House 2 was a typical house in Florida with a well-constructed roof and attic. The house owner installed a dehumidifier in the second floor of the house to control the moisture movement into the sealed attic. This helped maintain the humidity in the attic and inhibited saturating levels.

The control in temperature and moisture reflected in the roof sheathing moisture content (Figure 16). The PRAT simulated moisture content followed the trends in the seasonal variation of moisture but failed to capture the diurnal variation due to errors in modelling. The WUFI roof model did not consider hourly fluctuations in the roof air leakage and hence this affected the moisture movement from the attic to the exterior environment. The predicted and the measured moisture contents remained well below the 20% threshold for House 2 indicating the effect good workmanship has on the moisture content.

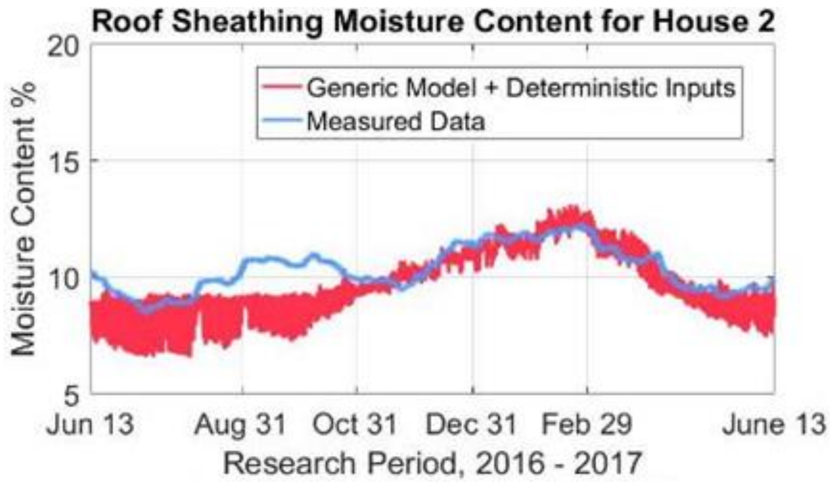

Figure 16. Roof sheathing moisture content – PRAT vs measured

House 4 located in Gainesville is a winter bird home, the house is occupied only during the winter. During summer, the thermostat is set to 80 which increases the relative humidity beyond 80% and occasionally over 95%. The high humidity provides suitable conditions for moisture to accumulate and this can be seen when the moisture spikes to 20% (Figure 17)

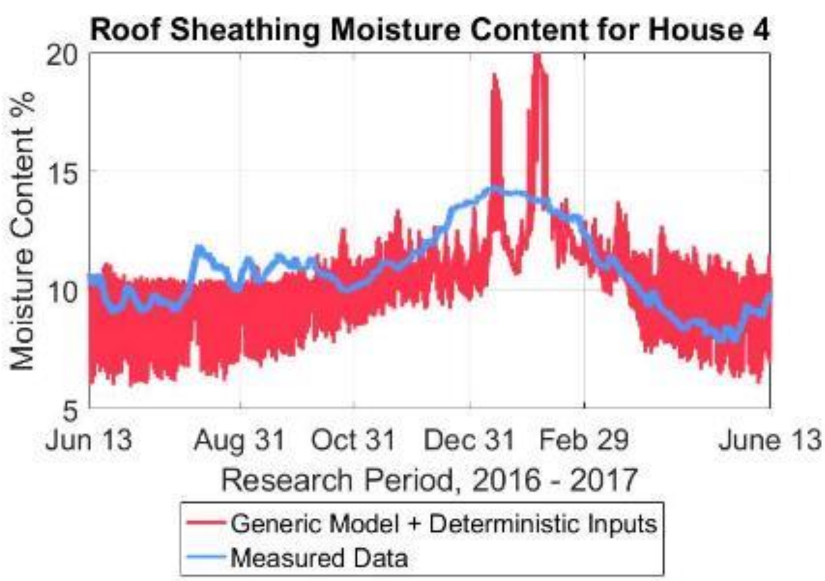

Figure 17. Roof sheathing moisture content – PRAT vs measured

However, this spike cannot be captured by the PRAT which considers regular movement in the house and attic, limiting the humidity in the attic below 80%. Hence the PRAT tool has some discrepancies in modelling which can be rectified in the future by taking into account exact field conditions.

Statistical analysis to measure accuracy in prediction

The error in prediction or the prediction accuracy is useful to quantify the predictive capacity of the PRAT toolkit. The coefficient of variation of the root mean squared error and the normal mean bias error are used to quantify the error in prediction. ASHRAE Guideline 14 says that the root mean squared error is a measure of variability in the data. For every hour, the error, or the difference in the paired data points is calculated and squared. The sum of all the squares is divided by the number of hours to produce the mean squared error (MSE). A square root of the result yields the root mean squared error (RMSE). The coefficient of variation of the root mean squared error (CV-RMSE) is calculated by dividing the RMSE by the mean of the measured data. Hence, CV-RMSE is a measure of the average deviations in the dataset and values under 30% are acceptable for model validation (ASHRAE Guideline 14). The normal mean bias error (NMBE) gives a measure of the overall bias in data. Bias in data occurs if a certain parameter consistently affects the outputs. NMBE values under 10% are accepted for model validation (ASHRAE Guideline 14).

Table 3. Accuracy prediction in PRAT numerical analysis

	House 2 – Venice		House 4 - Gainesville	
Error	CV-RMSE	NMBE	CV-RMSE	NMBE
Attic Temperature	7%	2%	6%	1%
Attic Relative Humidity	10%	3%	28%	19%
Sheathing Moisture	7%	1%	16%	5%

CONCLUSIONS

From the experimental analysis,

- The moisture content in the roof sheathing averaged around 15% for a 12-month period in four Florida houses with sealed attics
- House 1 retrofit with spray foam supposedly due to poor workmanship, had the highest attic air leakage leading to indoor thermal discomfort. The HVAC system was undersized and could not provide space conditioning effectively.
- House 4 is unoccupied during the summer and the thermostat is set to 80°F causing humidity levels above 80% for several hours potentially leading to higher moisture contents

From the numerical analysis,

- The Probabilistic Risk Assessment Toolkit can predict the indoor climate and the roof sheathing moisture content with good accuracy (Table 3)
- The Energy Plus model must be recalibrated to improve the prediction accuracy for house specific occupancy and climatic conditions
- The WUFI hygrothermal analysis is highly susceptible to the air changes per hour (ACH) from the attic to the outdoor. New data specific to houses should be generated to better match the roof sheathing moisture content occurring in the field.

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The value of campus-based solar demonstration homes for students, faculty, and communities

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Abstract

The interaction between individuals and their homes and between members of communities includes highly impactful social, economic, and ecological interfaces. Demonstration homes have the potential to elevate sustainability strategies as systems, and offer a unique setting for learning about the impact of our day-to day decisions on the world. Efforts to design and build sustainability-focused demonstration homes are expanding across the globe. This research investigates the value of three intentionally built demonstration homes as instruments for learning and community transformation. Three case studies are presented in which residential structures were designed and built in different campus settings as demonstration homes that embody the social, economic, and ecological systems in which they are placed. Observable patterns of process design, regional decision factors, and community interaction are traced through each case to inform three archetypal strategies for sustainable demonstration homes in support of the broad and creative adoption of the living learning laboratory concept. The results of this research can help colleges and universities explore methods to provide student experiences in sustainable technologies in a way that also helps consumers gain awareness and confidence in sustainability focused technologies and practices.

Introduction

Since its launch in 2002, the U.S. Department of Energy (DOE) Solar Decathlon competition has resulted in over one hundred solar homes built by teams from college and universities. Similar competitions in Europe, China, and Oman have also emerged and expanded this phenomenon. In 2010 the DOE received an Honor Award from the National Building museum in recognition for the Solar Decathlon's "commitment to educating architects, engineers, and builders—as well as the general public—about environmentally responsible, energy-efficient design" (Agnese, 2010). Building on this success the DOE launched the "Race to Zero" competition (formerly "Challenge Home") challenging university teams to advance energy-smart homes in realistic, usually local, housing market conditions. Concurrently, the creation of full scale residential renewable energy and energy efficiency labs have been pursued by NIST, the Emerge Alliance, utility companies, and private corporations to explore energy management technologies and building-to-grid integration strategies. To date, the emphasis and funding for these endeavors has been placed on the creation of these facilities. This research presents a longitudinal study of three solar homes created on three campus settings. The objectives of this research are to provide an overview of value adding processes that sustainability-focused on-campus solar demonstration homes can serve to colleges, universities, and communities. The research examines the impactful features of three structures that were built through a consistent approach adapted for three variable settings. The value-adding processes observed in each setting are examined to inform future efforts to leverage programs like the Solar Decathlon that are producing on-campus solar homes on colleges, universities, and communities.

Living Laboratory Strategy

The Living Laboratory concept has been broadly recognized as a strategy for EFS, Education for Sustainability (Bartlet and Chase, 2004, Brundiers et.al 2010, Brundiers and Wiek, 2011, and Mcmillin and Dyball, 2009). Essentially, the Living Laboratory strategy seeks to embrace campus grounds, regional eco-systems, and local social networks as assets for learning and experimentation in the advancement of sustainability (Riley 2013). The Living Laboratory concept is based on the premise that building capacity to truly understand, practice, and lead others in a new way of decision-making requires an immersive learning experience that dissolves the boundaries of classrooms, campuses, and communities. Immersive learning environments have the capability to create rich settings for education and research (Ma and Nickerson, 2006). The value of student-designed and built solar homes as teaching and learning resources has been the subject of some research and found to contribute greatly to the cultivation of valuable skills among architecture and engineering students (Iulo et. al 2014, Iulo 2013, ASHRAE 2007). Efforts to create immersive renewable energy and sustainable systems engineering labs have also been explored (Riley, et. al 2009), which also provides the theoretical foundation for the three cases presented in this research.

While referred to locally under variable names, the 2007, 2008, and 2013 case study homes were each designed and built as adaptations of the MorningStar concept, and as such, are referred to here as MorningStar I, II, and III respectively. The core team of project leaders and the individuals that contributed to one or more of the MorningStar projects are referred to throughout the document as co-creators.

Having built three MorningStar homes for different campus settings, the co-creators have benefited from a unique and instructive experience in the application of the Living Laboratory concept and the creation of intentional learning spaces dedicated to sustainability. The cumulative lessons of these projects are presented here in an effort to inform colleges and universities that are considering investments in residential teaching and learning structures on their respective campuses.

Research Approach

The goal of this research is to illuminate the unique characteristics of sustainability-focused demonstration homes as instruments for learning and transformation. An analysis of the impactful characteristics of three case study projects is presented in which a consistent set of design philosophies and principles are applied on a Research University campus, a Rural Tribal College, and an Urban Mixed-use Campus. The specific objectives of this research are to provide an overview of value adding processes that sustainability-focused demonstration homes can serve to colleges, universities, and communities and present the impactful design features of three demonstration homes that were built through a consistent approach. The pursuit of these objectives and the respective evaluation methods for each objective is presented below through an analysis of the MorningStar demonstration home projects.

The analysis of sustainability-focused demonstration homes presented here seeks to leverage the unique experiences of the research team over the course of a nine year program of design experimentation and application of commonly understood concepts of sustainable design. The use of concepts such as passive solar design, energy efficient envelope construction, and regionally appropriate materials are not unique but rather increasingly ubiquitous and essential. In this way, the homes described in this analysis are much like those built by students and faculty of colleges and universities around the world that are seeking to explore sustainability concepts in a tangible and hands-on approach through Solar Decathlon competitions or other similar events and initiatives. The specific features and technologies of the case study homes are presented with an emphasis on elements that are unique and distinctive. In addition to the description of technical features, the core principles that were applied across each project are described. This enables the evaluation of how these guiding concepts are pursued and individualized through the adoption of materials, methods, and technologies that are responsive to different settings.

Case Study Descriptions

This section provides an introduction to the three case studies upon which this research is centered. The guiding principles that were applied across all three cases are presented and includes the specific objectives, settings, and distinctive targeted features. The guiding principles of the MorningStar concept provide a common lens to the three demonstration projects. This provides a foundation to drive the development of unique and place-based design strategies for the specific settings. The unique conditions, objectives, settings, and defining characteristics of the three case study homes are summarized below.

MorningStar I (University Park, PA)

The first case study home, MorningStar I (MS-I) was built by a collaborative interdisciplinary team as an entry into the US Department of Energy 2007 Solar Decathlon Competition. This home was built in a modular construction process to enable transport to Washington, DC for the competition, and was then returned and reconstructed on a permanent site in University Park, PA.

Objective: To design and build a competitive entry for the 2007 DOE Solar Decathlon that will eventually be re-purposed as a laboratory and teaching facility on a University campus. The theme of this home and setting can be summarized as one seeking to be *competitive* in a focused and highly visible international competition.

Setting and Occupancy: The home is currently located on the campus of The Pennsylvania State University, a major research university, and serves as both a laboratory and a teaching resource for faculty in many disciplines. The home is used to host 2-3 learning experiences each week consisting primarily of students, university staff, and community members. Data is continuously gathered including real-time feedback for occupants on the use of energy in various systems in the home.

Defining characteristics: The defining characteristic of the MorningStar I is the inclusion of diverse and redundant high performance systems and technologies that enable the demonstration of sustainable building methods applicable to both new and renovation construction. These include high thermal mass, local building materials linked to passive solar design, geothermal, photovoltaic system (solar electric) and solar thermal integration, and automated controls for lighting, insulated blinds, and heating/cooling systems.

Unique features: The unique features of this home include a high level of instrumentation to inform competition performance and long term research on residential energy systems and controls. Since its establishment as a teaching resource, a new curriculum based on the home has been designed to engage students in the planning and implementation of immersive learning experiences for visitors to the facility as well as to engage students in home energy assessments in the community.

MorningStar II (Lame Deer, MT)

MorningStar II (MS-II) was designed and built through an integrated education and research program called the American Indian Housing Initiative (AIHI) in conjunction with the 2007 Solar Decathlon team. The home was built through a combination of a modular prefabricated core and on-site construction methods.

Objective: To demonstrate the portability of the MorningStar design concept and how an affordable and regionally appropriate version of the concept would take shape. The theme of this home and objective can be summarized as one seeking to offer *affordability* in a community with clear economic challenges.

Setting and Occupancy: MorningStar II is located on the campus of Chief Dull Knife College in Lame Deer Montana. The home serves as a much needed housing solution for visiting faculty who teach at the college and is typically occupied by various teachers during the fall, spring, and summer semesters. The home has been 90% occupied serving its intended use since completion in 2008.

Defining characteristics: The defining characteristics of the MorningStar II include the unique geometry intended to provide a visible departure from the common manufactured housing solutions in the region while also maximizing passive and active solar energy. In addition, the use of regional and durable materials is emphasized in response to the extreme temperatures and weather events in the mid-west.

Unique features: The unique features of this home include the use of load-bearing straw bale construction integrated with light wood trusses and structural insulated panels as window frame and roof elements. Natural ventilation and site-built insulated glazing are also employed to maximize natural light and low-cost cooling.

MorningStar III (Philadelphia, PA)

The third home in the series, MorningStar III (MS-III), was designed and built through partnership between faculty members and industry as a part of the DOE funded Grid-Smart Technology Application and Research (GridSTAR) Center.

Objective: To demonstrate and enable research on a wide array of smart grid technologies including home energy management systems, solar photovoltaic and thermal systems, and grid-interactive energy storage technologies. The theme of this home and objective can be summarized as one seeking to offer *broad appeal* to a variety of visitors.

Setting and Occupancy: The MorningStar III is located at the Navy Yard in Philadelphia. This strategic location takes advantage of the energy and sustainability initiatives underway through the redevelopment of this former military base by the City of Philadelphia, as well as the large unregulated electrical grid serving the Navy Yard that enables research and experimentation of smart grid technologies. The home is used for demonstrations and course-based visits, as well as business development meetings by project partners.

Defining characteristics: The defining characteristics of the MorningStar III include a combination of super-insulated modular construction and passive solar design coupled with active solar photovoltaic and solar thermal-integrated heating and cooling systems. The combination of these solutions helped achieve a LEED™ Platinum rating of the home and a Home Energy Rating Score™ of 21 (A score of zero = net zero energy home).

Unique feature: The unique feature of the home is the inclusion of a residential-scale micro-grid appliance that enables the management of solar PV generation, provision of back-up power to a critical load service panel, as well as the ability to participate in auxiliary grid services such as frequency regulation and peak load shifting. This system also serves as a training tool that helps various audiences gain familiarity with the rational and control logic applicable to micro grids.

Comparative analysis of systems and design attributes

The different attributes of the three MorningStar homes are summarized in Table 1. It is worth noting the high variability of size and cost for each structure. MorningStar I was limited to 800 GSF by the competition regulations. This resulted in low economies of scale and a high cost per square foot. By contrast, MorningStar II was built using volunteer labor to inform a community-built approach such as those employed by Habitat for Humanity. MorningStar III was built using conventional modular construction, but with time taken to integrate multiple emerging technologies into the design, operation, and instrumentation of the home. The setting and occupancy of each project also differs and provides a diverse perspective of the potential roles and values of homes across different conditions. Each home was built through unique research and education initiatives that were considered to be strategic in contributing to the long term sustainability of the projects. The construction methods, materials, and technical systems are largely responsive to local climate and availability of reliable technologies and where supportive of modular or semi-skilled low cost construction labor to reduce costs.

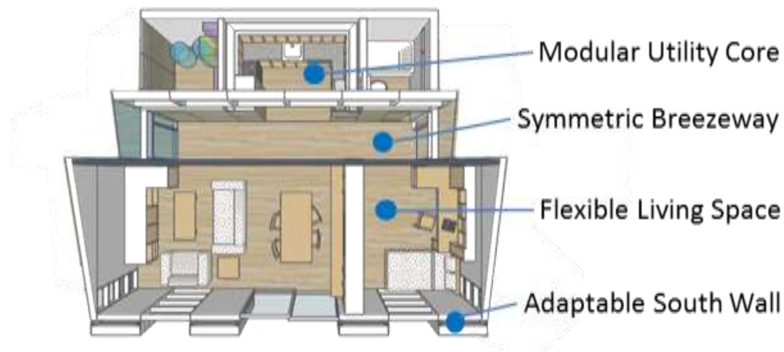
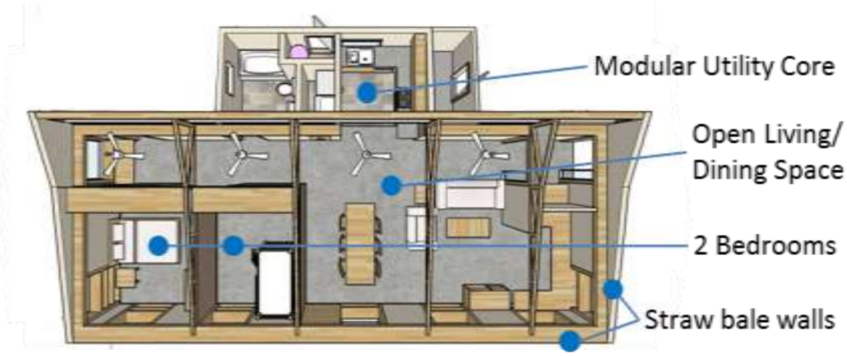
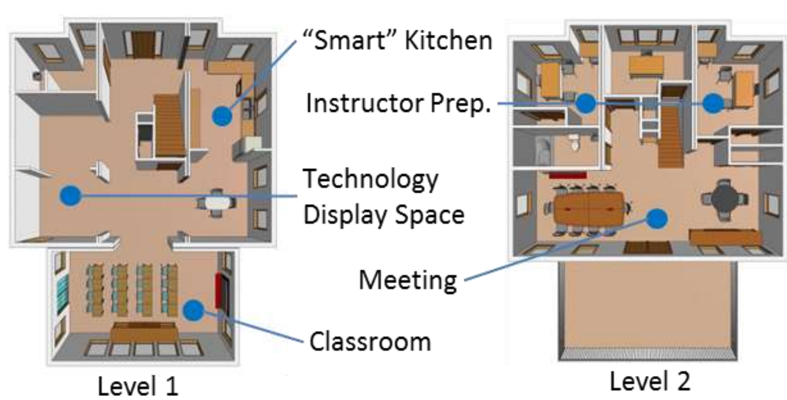
The high value placed upon modular and prefabrication strategies in each project is based upon the contribution of these techniques for optimizing investment in skilled labor, reducing material waste, and enabling scalability of sustainable technology and systems integration (Luo, 2012 and Iulo, 2009). Yang (2009) found prefabricated housing to reduce energy usage by 70%, raw materials usage by 50%, construction waste by 40%, on-site labor by at least 50%. New technologies such as solar photovoltaic and solar thermal systems require skill sets to install and maintain that are often scarce. Installing these technologies in a factory setting can help lower the costs of these unique skills. A demonstrative strategy in which both of these economies was observed was pursued in the construction of MorningStar III, in which solar modules were installed both in the factory and on site for comparative purposes. This experiment resulted in the observation of an 80% reduction in labor cost in the factory setting in comparison to installation of the solar modules in the field after the home was erected.

Table 1: Case Study Home Features

Attributes	MorningStar I	MorningStar II	MorningStar III
Image			
Location	University Park, PA	Lame Deer, MT	Navy Yard – Philadelphia, PA
Size (GSF)	799	1180	2260
Cost/SF	$438	$127	$199
Date completed	September, 2007	July, 2008	October, 2013
Occupancy / Use	Outreach and education program + intermittent occupancy	Visiting faculty housing resulting in 80-90% occupancy	Outreach and education program, simulated occupancy
Campus Setting	Large land grant university	Rural tribal college	Urban satellite campus
Strategic program integration	University Center / 2007 Solar Decathlon	Collaborative education and research initiative: American Indian Housing Initiative (AIHI)	Integrated education and research center: GridSTAR Center
Website	www.morningstar.psu.edu	www.engr.psu.edu/greenbuild	www.Gridstarcenter.psu.edu
Construction method	Modular core + Structural Insulated Panel	Modular core + Structural Insulted Panel and Straw bale	Modular components (7) with 2x8 framing
Electrical system	Grid connected solar PV	Grid connected solar PV with battery back-up	Grid connected solar pv with grid interactive battery back/critical load panel
Heating system	Ground source heat pump + electric boiler with solar thermal boost	Propane boiler with solar thermal boost	Air-source heat pump with solar thermal boost
Cooling system	Ground source heat pump / natural ventilation	Natural ventilation	Air-source heat pump with solar thermal boost
Unique features	Reclaimed materials, competition-grade instrumentation, training curriculum	Community building design features, high-mass envelope, site-built glazing, fulltime occupancy	Factory-installed solar PV, grid-interactive energy storage, DC powered mini-split AC
Common Features	Passive solar design, Modular construction, Regionally appropriate materials and methods, Integrated solar electric and thermal systems, Design-for demonstration		

Table 2 summarizes the geometry and assembly strategies of the three case study homes to illustrate the different approaches to design and construction pursued, and the methods by which prefabrication and modularization techniques were adopted.

Table 2: Geometry and Assembly Strategy

<table>
<tr><th>Description</th><th>Diagram</th></tr>
<tr><td>MorningStar I:
Modular utility core houses kitchen, bath, and technical systems.
Structural insulated panel wall and roof system.
North-facing insulated translucent glazed breezeway links North core and South Living space.
Adaptable south wall can be reconfigured for day/night and seasonal sun angles.</td><td>
</td></tr>
<tr><td>MorningStar II:
Modular utility core built off-site.
Load bearing straw bale walls and structural insulated panel roofing system.
North-facing insulated translucent glazed breezeway links North core and South Living space.
Flexible layout designed to host small groups.</td><td>
</td></tr>
<tr><td>MorningStar III:
Modular two-story construction with 2x8 framing and experimental high density loose insulation.
Micro grid appliance and heating and cooling system displayed in living space to support research and instruction.
Cape Home architecture modified to accommodate teaching and learning for instructors.</td><td>
</td></tr>
</table>

As structures intended to be demonstrative to community audiences while also serving as living laboratories the cases can inform future investments. An activating force exists to integrate as many sustainable technologies as possible into the structures. The restraining force needed to balance this tendency is typically the cost limitations for the project itself. Moreover, expensive and extravagant technology demonstrations has the risk of appearing too expensive to others who may consider replication of the home or adoption of the featured techniques and systems. In wrestling with these activating and restraining forces, the guiding principles emerged as valuable instruments for co-creators of the three MorningStar homes to make decisions that respond to unique settings and project conditions. While these settings and conditions are describes later, the principles applicable to the selection of technologies and systems are presented here along with the resulting value-adding features that were introduced and integrated into the projects.

While the geometry and architectural features of the home are largely a product of the setting and project conditions, a significant number of decisions need to be made about what technologies and systems to integrate into a demonstration home. In making these decisions, an approach is taken to consider the *value-adding processes* that systems and features offer to the project. Value adding processes may include the performance of key functional purposes such as heating and cooling. In the case of demonstration projects, a key value adding process is the contribution of systems and features towards advancing the understanding of sustainability concepts by community members, or fulfilling unique opportunities of the deployment setting. The aspiration to maximize teaching and learning opportunities was the central guiding principle for each project and pursued within the limitations of project resources and conditions.

Table 3 presents a summary of the systems ultimately selected for each home and the degree to which they were deployed in terms of an exemplar application which is meant to underscore a key approach verses a common application which is intended to demonstrate appropriate, accessible, and repeatable strategies.

MorningStar I project team sought to bring the full weight of the university upon entry in the Solar Decathlon Competition. Aggressive fundraising and manufacturing partnerships were used to enable a near blank-check to the design-build team, with the stipulation that the project be competitive in the event. Decisions were made to integrate features deemed to be functional, impressive to subjective judging, and to serve the long-term mission of the facility as a laboratory and a teaching instrument. The unique architecture of the home reflects the geometry and colors of neighboring athletic stadiums and venues in proximity to the home's permanent location. As a result, the MorningStar I includes a densely concentrated set of sustainability features and systems. In contrast, MorningStar II was approached in a much different manner with a primary goal of demonstrating the affordability and transferability of the MorningStar concept. Decisions were made to include solar integrated mechanical and electrical systems in a cost-saving prefabricated core and in a manner that could enable minimal care and maintenance from what was expected to be full time occupancy by short-term tenants. Envelope systems and materials were selected to enable the participation of a high percentage of low-cost volunteer labor. Geometry was carefully considered to maintain simplicity, but to demonstrate a clear departure from the dominant manufactured housing vernacular in the community. MorningStar III was built through a grant from the U.S. Department of Energy which enabled a significant number of value-adding technologies and features to be integrated into the home. In particular grid interactive systems were added to create advanced control features in support of smart grid strategies. The architecture of the home responded to the highly visible (and somewhat traditional) vernacular of the urban campus location and also sought to reflect modern home building techniques and materials. While expensive to build as a one-off prototype, manufactured housing processes and practical systems and technologies were included to respond to the value of affordability of an "average" home buyer. With no permanent occupancy planned, the home was built to a residential building code with every effort made to gain an understanding of how selected technologies and features would be made available in an affordable modular home building process.

Table 3: Value Adding Processes of each home based on features and systems deployed

Value-adding processes enabled as demonstrative sustainability-focused systems and features	**MS-I** Research campus (*competitive*)	**MS-II** Rural campus (*affordable*)	**MS-III** Urban Campus (*broad appeal*)
Passive solar design concepts/geometry	●	●	○
Efficient heating and cooling systems	●	●	●
Passive ventilation	○	○	
Daylighting	●	●	○
Flexibility / reconfiguration	●	○	
Prefabrication / modular assembly	○	○	●
Unique insulating materials	●	●	●
Efficient glazing systems	●	○	○
Insulating window treatment	●	○	○
Lighting control / dimming systems	●	○	●
Regional materials selected	●	●	○
Local businesses engaged	●	●	○
Unique geometry responding to setting	●	●	
Active solar photovoltaic system	●	○	○
Active solar thermal collection	●	○	○
Battery Energy Storage	●	○	●
Electric vehicle infrastructure integration	●		○
● Exemplar demonstration ○ Common demonstration			

In all of the projects, decisions were made to include exemplar demonstration systems or features when they were considered to be vital to the intention of the project. Other systems were deployed in a manner that would be appropriate for most homes in the respective regions. In some cases, due to cost constraints and the intended messages desired, some systems were not included. In the case of MS-I, built for the Solar Decathlon competition, a significant number of value-adding systems and features were integrated into the design including many in an exemplary manner. MS-II however, was built with a core value of affordability including fewer exemplar systems, while still retaining a significant number of features enabled by prefabrication techniques and locally available building methods. MS-III's focus on a prominent location resulted in the inclusion of more conventional features, but with significant investments made in grid-interactive systems that were central to the purpose of the project. The resulting characterizations of the three homes as competitive and high performing (MorningStar I), affordable (MorningStar II) and broadly visible and appealing (MorningStar III) are useful in highlighting the results of design decisions that responded to the different core purposes of the respective projects.

Discussion and Observations

The evaluation of the unique and collective impacts of the three homes yields insight into the potential value of sustainability focused demonstration homes in communities as well as the various strategies for occupancy and use that may be pursued. Three archetypal models emerging from these observations are offered to encourage further exploration and collaboration among colleges, universities, and funding agencies seeking to invest in the advancement of sustainable housing and energy efficiency teaching, research, and outreach activities. Each model elevates a potential focused outcome that may be pursued through the creation of on-campus sustainability-focused demonstration homes on or in proximity to colleges and universities and the communities they serve. The three archetypes are presented herein for consideration as a strategic focus for a current or future on-campus demonstration home.

Conclusions

The development of sustainability-focused homes on the campuses of college and universities is expanding on a global scale. The effort and cumulative effects of these initiatives has the potential to have significant and profound impacts on the teaching, research, and service missions of these institutions. Currently however, most investments in these projects are focused on the creation of the facilities, and less so on leveraging the long-term value of the facilities.

This research seeks to elevate the value of campus-based demonstration homes as catalysts for change. It specifically seeks to highlight the key activating and restraining forces pertinent to such demonstration projects. These forces can be reconciled in a way that provoke and inspire the expanding global community of college and university teams engaged in these pursuits. The unique privilege of building multiple homes as immersive living laboratories in multiple settings has revealed useful lessons that can inform future efforts in integrating renewable energy and sustainability into the fabric of education and research programs.

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Role of BIM in Designing Zero-Net Energy Homes

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ABSTRACT

A zero-energy home is known to be capable of balancing its own energy production and consumption close to zero. Development of low-energy homes and zero-net energy houses (ZEHs) is vital to move towards energy efficiency and sustainability in the built environment. In order to achieve zero or low energy targets in homes, it is essential to use the design process that minimizes the needs for active mechanical systems. In this respect, passive design strategies and user collaboration/behavior scenarios can play a key role in achieving the objectives and targets of zero energy houses. Furthermore, building information modeling (BIM) plays a key role in advancing methods for architects and designers to communicate through a common software platform, analyze energy performance through all stages of the design and construction process, and make decisions for improving energy efficiency in the built environment. This paper reviews the literature relevant to the role of BIM to help simulating the energy performance of residential homes to more advanced levels, and in modeling the integrated design process of zero-net energy houses. The study proposes a number of potential decision-making strategies to achieve zero-net energy houses within BIM-based environment analysis process. This work also highlights key factors influencing zero-net energy houses associated with utilization of advanced building technologies.

INTRODUCTION

Achieving the zero-net energy houses (ZEHs) status is one of the most fundamental goals of sustainable development. ZEHs can play a significant role in reducing CO_2 emissions and environmental impacts. These houses are considered as self-sufficient buildings that can provide their own energy needs from renewable sources produced on-site without connecting to energy networks.

The vision of ZEHs can contribute to address the sustainability objectives and sustainable value chains in the built environment. For example, it is possible to predict the development of sustainable value chains when zero energy has been achieved in buildings. Sustainable value chain is defined as a holistic perspective of supply chain processes and methods that uses environmentally friendly initiatives for improving the existing environmental policies and reducing energy needs. This process can be expressed in a graphical format which sustainable value chains and zero energy level are appeared as curve line and straight line (basis) respectively due to increase in energy efficiency of buildings (Figure 1).

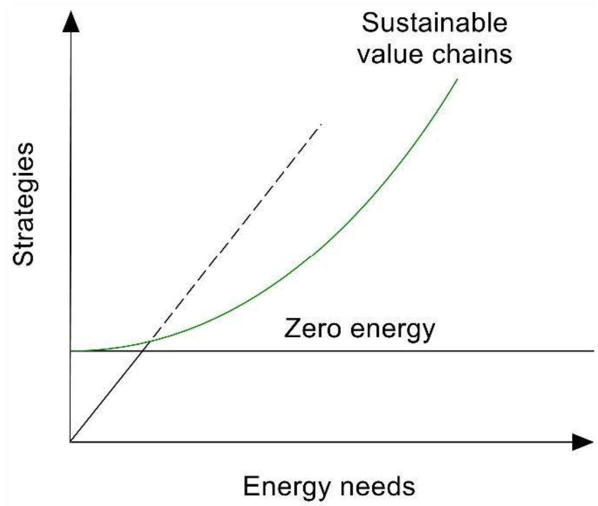


Figure 1. Overview of relationship between zero energy and sustainable value chain.

ZEHs have a leading role within the vision of a future city, as these homes can contribute significantly to reducing energy consumption and carbon dioxide emissions in cities. In addition, they are able to address challenges regarding renewable energy generation, energy management and carbon footprint. In fact, ZEH is a building concept that provides its own energy needs (including electricity) through renewable energy-based off-grid systems (Figure 2). According to Laustsen (2008), "*Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid*".

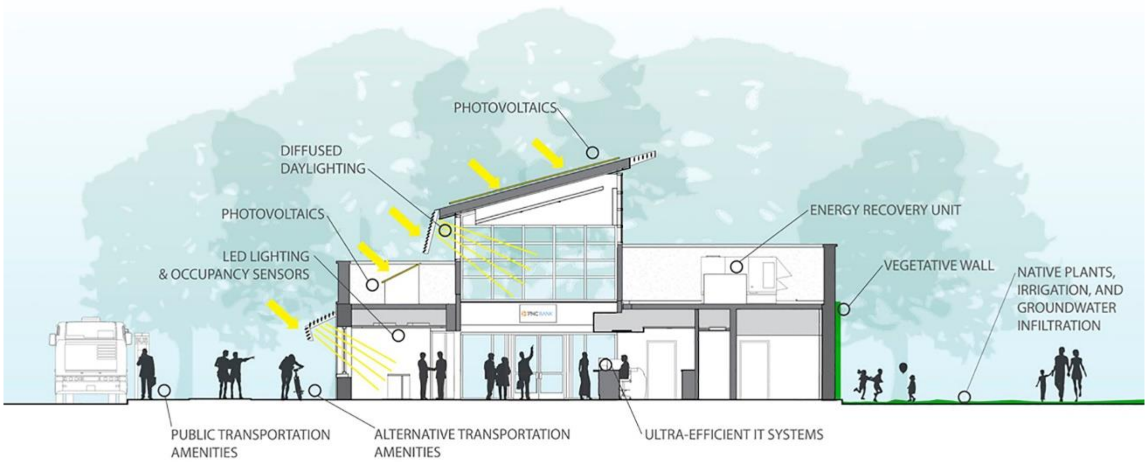


Figure 2. An example of a zero net energy building-the PNC Bank, Florida. U.S. Department of Energy (2015).

According to a study by Voss et al. (2011), a ZEH should use off-grid energy technologies and benefit from renewable energies for its own needs. The U.S. Department of Energy (DoE) building technologies program also described a zero energy house as a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies. In this context and according to Sartori et al. (2012), zero energy balance can be shown by the following equation:

$$\text{ZEH} \Rightarrow \text{Energy Balance: (weighted supply)} - \text{(weighted demand)} = 0 \quad (1)$$

where weighted supply and weighted demand refer to the sum of all exported energy (generation) and the sum of all delivered energy (load) respectively. A ZEH can be achieved through the use of efficient thermal insulation and renewable energy generation. However, due to challenges in achieving ZEH status based on conventional energy supply systems, it is important to use effective energy efficiency strategies at each stages of the design and construction process. In this respect, building information modeling (BIM) has been identified as an effective tool for designing and evaluating energy efficiency targets (Habibi, 2017). BIM can be used in all stages of building a house. It can play a key role in improving efficiency and building performance throughout the entire life cycle. In a study by Guo and Wei (2016), BIM was used to determine the most energy-efficient building design possible. The study showed that BIM can develop a highly accurate simulation platform for the energy consumption of buildings. The demand for energy-efficient housing designs through the use of the BIM methodology is continuously increasing. BIM can help users to model and simulate all aspects of the building (planning, design, and construction). With the aid of BIM tools, different design strategies can be easily achieved and assessed during the early stages of a project. In addition, BIM allows users to choose building systems that optimize energy usage.

A study by Ceranic et al. (2015) was carried out to explore methods and technologies for integration of sustainable design analysis with BIM. According to the US GSA (2015) use of BIM-based energy modeling has potential benefits that include accurate energy performance analysis, lifecycle cost analysis, and opportunities for monitoring of actual building performance. A study by Eleftheriadis (2017) focused on recent developments of BIM-based design processes in both the structural engineering and the life-cycle energy areas.

As mentioned before, the most common concepts of a zero-net energy house focus on increasing renewable energy generation rather than using coal and fossil fuel as energy resources. In this context, the use of BIM for optimizing energy consumption with alternative renewable energy sources can be considered an efficient approach to design and construct a ZEH.

SUGGESTED METHODS TO PROMOTE ZEHs

In order to promote ZEHs, it is necessary to develop novel methods of increasing energy efficiency and reducing energy demand through low-energy technologies and renewable energy sources. While laboratory experiments on ZEHs are the most costly approach in terms of time and space for design and validation, BIM-based tools can have promising impact in designing affordable ZEHs and reducing experimental costs. To determine the functionalities of a BIM-based tool for designing ZEHs, it is important to review definition and calculation methodologies, which can be used to measure and optimize energy supply systems. The combination of optimization algorithms with BIM-based tools can be used to describe the relationships between energy efficiency and demand response. In this context, Hamdy et al. (2016) compared the performance of some multi-objective optimization algorithms for ZEHs design problems. They provided an overall view of the performance and behavior of these algorithms based on which researchers can make a choice for their specific problem. In the context of developing the ZEH concept, Iturriaga et al. (2017) proposed a general optimization model for the design and operation of energy supply systems.

The most important design variables that affect ZEHs are either energy related or economic related. The multi-objective optimization process is considered an important method in the decision-making process for improving energy and economic performance of ZEHs. In this context, building envelope is one of the most important components of a ZEH. To achieve zero-net energy consumption, it is important to focus on creating a highly insulated and airtight envelope. The optimization of building envelope components for ZEHs plays an important role in achieving zero energy balance and efficient energy use. Ascione et al. (2015) developed an optimization method for energy performance and thermal comfort of the building envelope by means of a genetic algorithm implemented in MATLAB. In another study, Ascione et al. (2016) developed methods for the use of dynamic energy simulation tool and multi-objective optimization algorithm to reach ZEH objectives in four different cities of the Mediterranean climate. They sought to provide the best compromise among optical and thermal physical properties of building envelope in simple residential house.

It is clear that building envelope components such as walls, fenestrations, roof and foundation make a significant contribution to overall household energy consumption and are important elements of operation to the ZEH goal. A recent study by Krasny et al. (2017) proposed construction of ZEHs with a bio-based insulating envelope as one solution. The study sought to understand the environmental performance of straw bale house. An energy analysis was carried out through BIM and results showed that energy use intensity for bio-based ZEH is half of this figure for the concrete house. The use of BIM provides many benefits associated with improving energy performance and deploying zero energy building envelope components. To understand the importance of BIM-based tools for designing ZEHs and to develop cost-effective energy efficiency methods, it is important to focus on BIM implementation process in design-build projects.

METHODS FOR DESIGN AND ANALYSIS OF ZEHs

In order to highlight the importance of BIM role in designing ZEHs, a case study house was examined to investigate the feasibility of the proposed method. The house for this case study is a stand-alone residential structure located in the city of Philadelphia, Pennsylvania (Zone 5) in which its latitude is 40.1 ° N, the longitude is 75 °W. The climate conditions of this case study house is based on the Typical Meteorological Year weather profile dataset for Philadelphia, Pennsylvania that can be downloaded from the U.S. Department of Energy website (Figure 3).

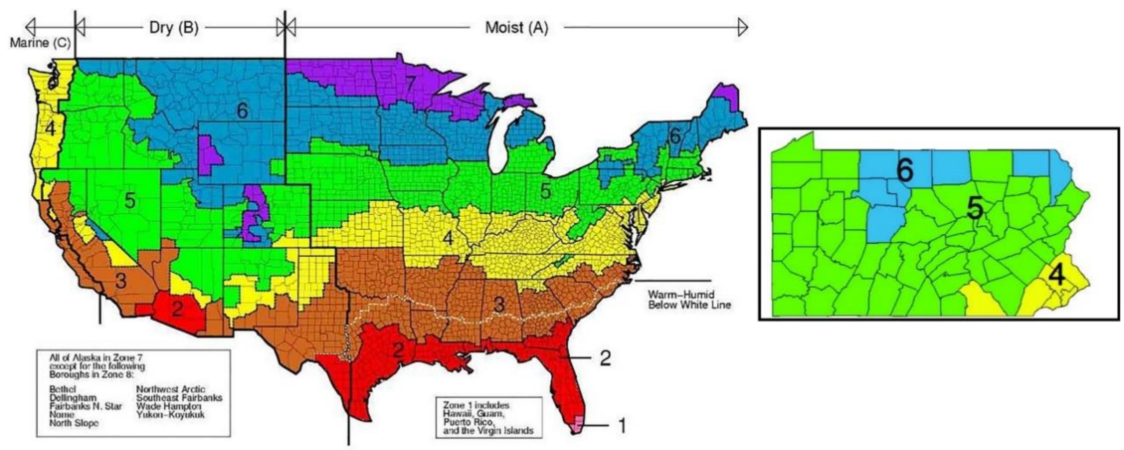


Figure 3. International Energy Conservation Code (IECC) climate zone map.

The case study house was constructed from building elements made out of wood that allows faster building turnaround. The total area was 175 m^2, built by off-site constructed building elements (Figure 4). The house is considered as a base case in order to make a proper comparison with ZEHs performance. The main focus is on reducing thermal loads through the building envelope components and to develop a ZEH that will contribute to improve energy efficiency and new solutions for housing in the built environment. In this study, minimum thermal envelope requirements of case study house was examined.

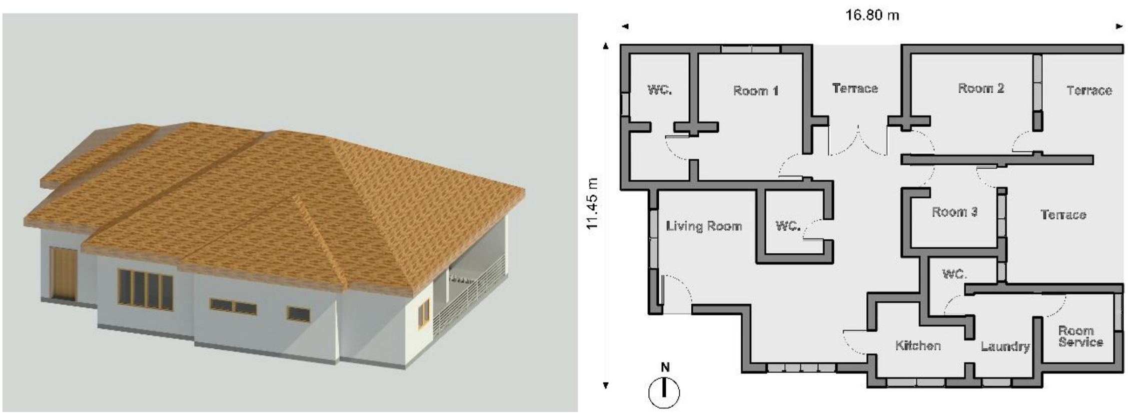
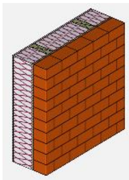
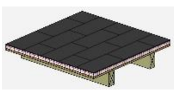
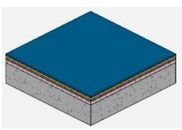


Figure 4. 3D view of case study house and its plan.

For the case study house, energy process analyses were conducted with BIM through building performance simulation (BPS) tools. This study has been performed to investigate the influence of BIM at early stages of design and focuses on the use of efficient and cost-effective methods for designing ZEHs. Therefore, the most important strategies are considered to reduce energy consumption and increase energy efficiency by means of BIM and BPS tools.

In order to analyze energy performance of the case study house, a Revit-based BIM process was performed for the current application. The method is applied for modeling base case and importing into Ecotect 2011 (Autodesk, 2017) , which is a building energy analysis software and is used for analyzing building thermal, light and acoustic conditions. In this context, Revit-based model has been exported to Green Building XML (gbXML) language which allows the transfer of building properties stored in BIM to BPS tools. Furthermore, Opaque 3.0 software was used to calculate U-value, time lag, and decrement factor for building envelope components (Table 1). It can also be used to calculate the heat gain or loss through the surface. The primary objective was to determine heating and cooling loads of case study house, therefore, the process simulations were performed with the Ecotect software for its initial energy performance (Figure 5).

Table 1. Thermal properties of each building envelope component.

Component	Layers	Thickness [mm]	U value [W/ (m^2 K)]	R- value [m^2K/W]
Wall	Gypsum board	10	0.283	3.53
	Studs (wood) +Insulation 508x152.4mm	152.4		
	Fiberboard Sheathing	12		
	Brick veneer	101.6		
Roof	Studs (wood)	101.6	0.597	1.67
	Fiberboard Sheathing	12		
	Polyurethane Foam	25.4		
	Asphalt shingles	3.2		
Ground floor	Concrete slab	150	0.871	1.51
	Expanded polystyrene (EPS)	25.4		
	Fiberboard Sheathing	12		
	Plaster	12.7		
	Carpet	12.7		
Windows	Doubled glazed (Low-E coating) with vinyl frames		U value [W/ (m2 K)] =2.260	
Doors	Solid wood		U value [W/ (m2 K)] =1.830	

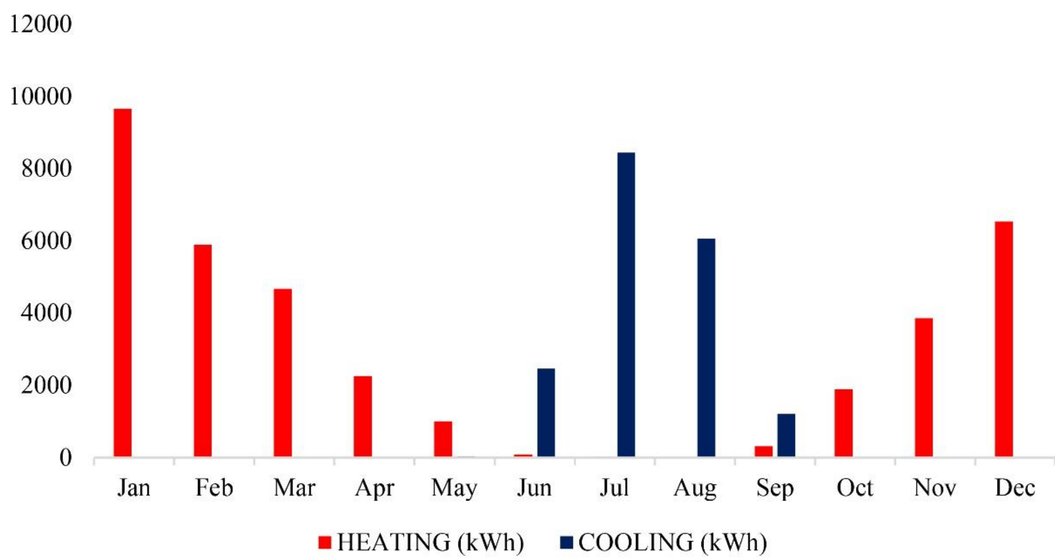


Figure 5. Heating and cooling load results of case study house.

The heating loads of a house are mainly related to conductive heat loss and air leakage through building envelope components. Furthermore, transparent envelope components, such as windows have a large influence on cooling loads. The results of the case study house indicate that total heating loads (36,200 kWh) are higher than the cooling loads (18,220 kWh). Furthermore, the maximum heating load (9,660 kWh) is higher than the maximum cooling load (8,440 kWh) with a temperature range between 21 °C and 26 °C.

In the context of energy performance, it is important to determine whether the case study house meets the Department of Energy's zero energy ready home requirements (Table 2). Furthermore, in order to upgrading energy performance of case study house to ZEH level, a field-sensitive analysis based on local climate condition is required. For example, Pennsylvania has three climate zones (Zone 4, 5 and 6) as defined in the IECC (energy) and IRC (structural, plumbing, etc.), therefore, it is necessary to upgrade existing elements of base case model in accordance with applicable standards and procedures (Table 3).

Table 2. ZERH Envelope Requirements according to 2012 IECC levels.

	R-Value
Ceiling	R-49
Wall	R-20 or 13+5
Floor	R-30
Slab	R-10 for 2 ft

Table 3. Insulation and Fenestration Requirements by Component (2012 IECC).

Climate Zone 5 and Marine 4	**U Factor**
Fenestration	0.32
Ceiling	0.026
Wood Frame Wall	0.057
Mass Wall	0.082
Floor	0.033
Basement Wall	0.050
Crawl Space Wall	0.055
Roof (R-30)	0.033

For design and optimization of ZEHs, an accurate use of renewable energy resources is necessary. However, according to the current method, building envelope retrofit strategies are considered to achieve ZEHs. Kamel and Memari (2016) highlighted that adding insulation to building envelope components and replacing windows are considered practical energy retrofit scenarios. Omrany et al. (2016) have highlighted some retrofit solutions of envelope walls such as Trombe walls, autoclaved aerated concrete walls, double skin walls (DSFs), phase change materials (PCMs) and green walls. The selection of appropriate materials for building envelope components has an important driving-force in promoting energy efficiency. In this context, phase change materials (PCMs) are emerging for use as thermal insulating materials in order to improve the energy performance of buildings. PCMs are able to balance between energy demand and energy supply and reduce the heating and cooling loads. They are capable of storing thermal energy as latent heat. Some authors, such as Lv et al. (2006, 2007) have used the liquid PCM immersion into shaped building materials. From a building envelope design point of view, it is important to use appropriate PCMs due to their different chemical natures and temperatures. PCMs are classified based on their physical characteristics such as organic and inorganic. Organic PCMs are defined as paraffin and non-paraffin types and inorganic PCMs are hydrated salts. According to IEA (2005), a comparison between organic and inorganic materials for heat storage is shown in Table 4.

Table 4. Comparison of organic and inorganic PCM for heat storage.

Organics	**Inorganics**
Advantages -No corrosiveness - Low or no undercooling - Chemical and thermal stability	**Advantages** - Greater phase change enthalpy - Sub cooling
Disadvantages - Lower phase change enthalpy - Low thermal conductivity - Inflammability	**Disadvantages** - Subcooling - Corrosion - Phase separation - Phase segragation, lack of thermal stability

Cellura et al. (2014) and Hachem et al. (2011) highlighted that the use of latent energy storage systems can be considered as one of the solutions to the energy mismatches in ZEHs. In this context, latent heat thermal storage (LHTS) systems with PCM in comparison with sensible heat storage systems have high energy storage capacity, which can result in a great adaptation to renewable energies (Jeon et al. 2012). It is clear that the development of LHTS system with PCM can play a crucial role to take advantage of renewable energy sources such as solar radiation, solar heat, and wind. For example, PCMs have a large heat capacity and can store large amounts of energy in building envelopes leading to a decrease in energy consumption and production and an increase in energy storage density and indoor thermal comfort (Figure 6). Furthermore, they are helpful for the effective use of passive cooling and heating strategies and ventilation in buildings.

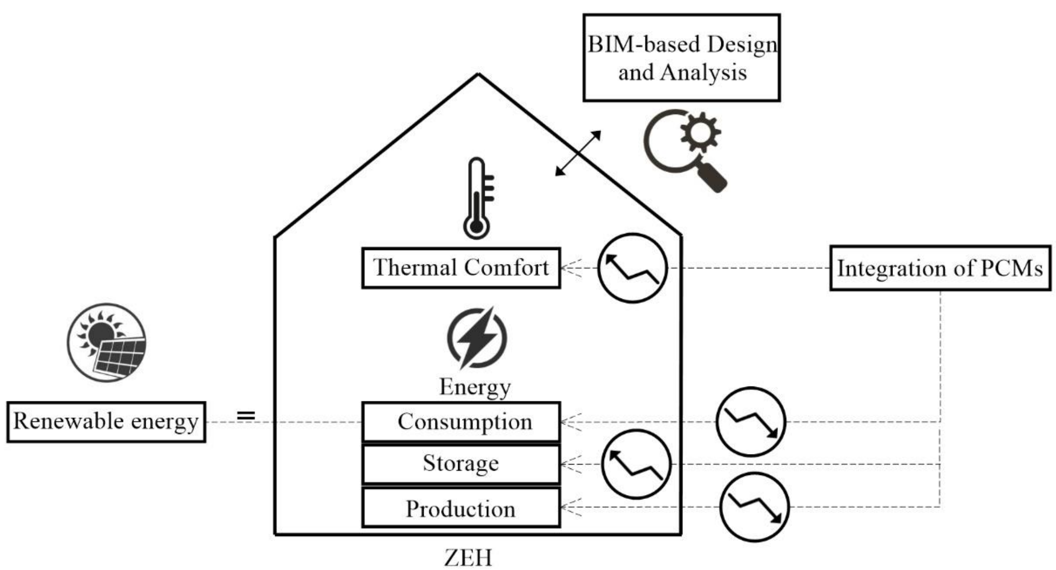


Figure 6. The relationship between a ZEH and potential of PCMs and BIM.

DATA AND RESULTS

In order to determine the potential influence of the PCM and renewable energy sources on the case study house, it is necessary to validate their behaviors to reduce energy consumption. In this context, simulations were performed through Ecotect and Opaque software. At the first step, the PCM layer (high-density polyethylene (HDPE) having a phase change temperature range between 21 °C and 26 °C) was assumed to be installed within the envelope of the case study house including the external walls, roof, and floor. In addition, thermal material properties and U- values were calculated by the Opaque software and transferred into Ecotect to run the analysis. It is clear that the thermal resistances can be affected by incorporation of the PCM. This can be useful in reducing the need of mechanical ventilation systems and energy demand. It important to note that in the simulation process of case study house, a thermal comfort band between 21 °C and 26 °C, which are the indoor design temperatures for heating and cooling has been defined. Furthermore, it is assumed that active mechanical systems have been used to provide comfort and adequate heating and cooling from January to December. According to simulation results, it was found that PCM cladding is useful in reducing energy demand and achieving energy conservation. BIM energy analysis showed that the PCM incorporated in building walls, roof and floor can reduce the total annual cooling and heating energy consumption (kWh) from 54,420 (kWh) to 50,920 (kWh) and save 6.87% of the energy (Figure 7). Analysis of the results revealed that PCM cladding has the potential to achieve efficiency in heating loads than cooling loads.

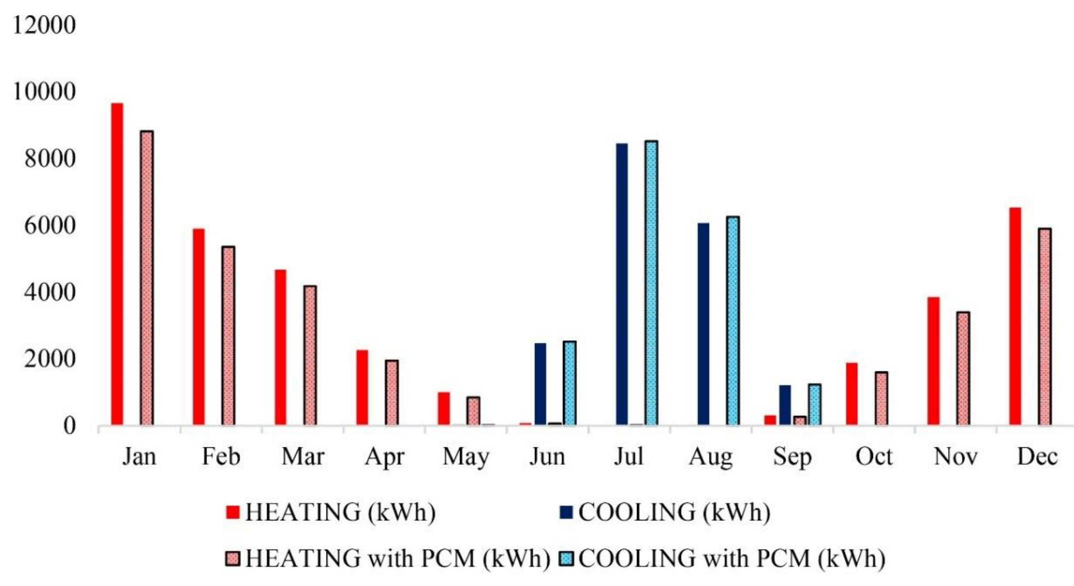


Figure 7. The heating and cooling load results of case study house with PCM.

As part of the study presented here, it is desirable to integrate BIM-based model in the design process of a ZEH based on phase change energy solutions and renewable energy sources. Although some different scenarios can be used to verify these solutions, BIM-based model analysis can help meet building energy needs and the development of ZEHs efficiently in terms of time and costs. Meeting the case study house energy needs and delivery of a ZEH requires development of renewable energy sources. In this context, solar energy is more affordable and accessible and can be used to generate a portion of the house's power need. Photovoltaics (PV) are one of the primary technologies for harnessing solar energy. They are still widely installed on sloped or flat roofs to convert sunlight into electricity. The reasons for choosing this type of technology includes their high efficiency and possibility to capture sunlight from all directions. In order to calculate the solar PV energy output of a photovoltaic system, it is required to find the global annual irradiation incident on PV panels with specific inclination (slope, tilt) and orientation (azimuth). In this context, the electricity generated as the output of a photovoltaic system is determined by the following equation:

$$E = A \times r \times H \times PR \quad (2)$$

where, E = Energy (kWh), A = Total solar panel Area (m^2), r = solar panel yield or efficiency (%), H = Annual average irradiation on tilted panels (shadings not included), and PR = Performance ratio, coefficient for losses.

In this respect, the annual average irradiation is defined to be the solar radiation incident on a given surface area and vary according to local situations. For example, Philadelphia has annual average irradiation of approximately 1469 kWh/m^2 (Figure 8), while Berlin has 1030 kWh/m². It is important to note that the potential annual electricity generation from PV panels depends on their direction and tilt in which they get a maximum insolation throughout the day. Therefore it is important to orient solar panels to get maximum amount of solar radiation.

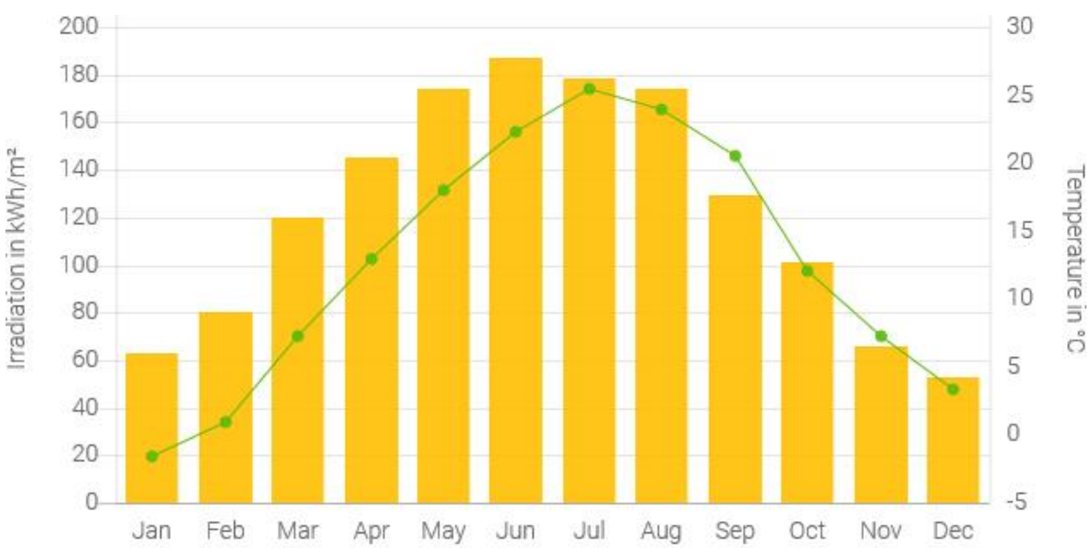


Figure 8. Annual global irradiation in Philadelphia, Pennsylvania (PVSOL online, 2017).

In order to identify solar energy potentials that can be absorbed by the surfaces of the case study house, a sensitivity analysis was also carried out through BIM-based collaboration (Figures 9 and 10). This process can be helpful especially in determining the optimal PV power systems needed to meet expected electricity demand during a defined period. Simulation results revealed that the most and least solar energy absorption by the surfaces of the case study house were by the roof and the floor, respectively. It was also found that total annual average irradiation (incident solar radiation) of the case study house was not more than 1245 (kWh/m^2).

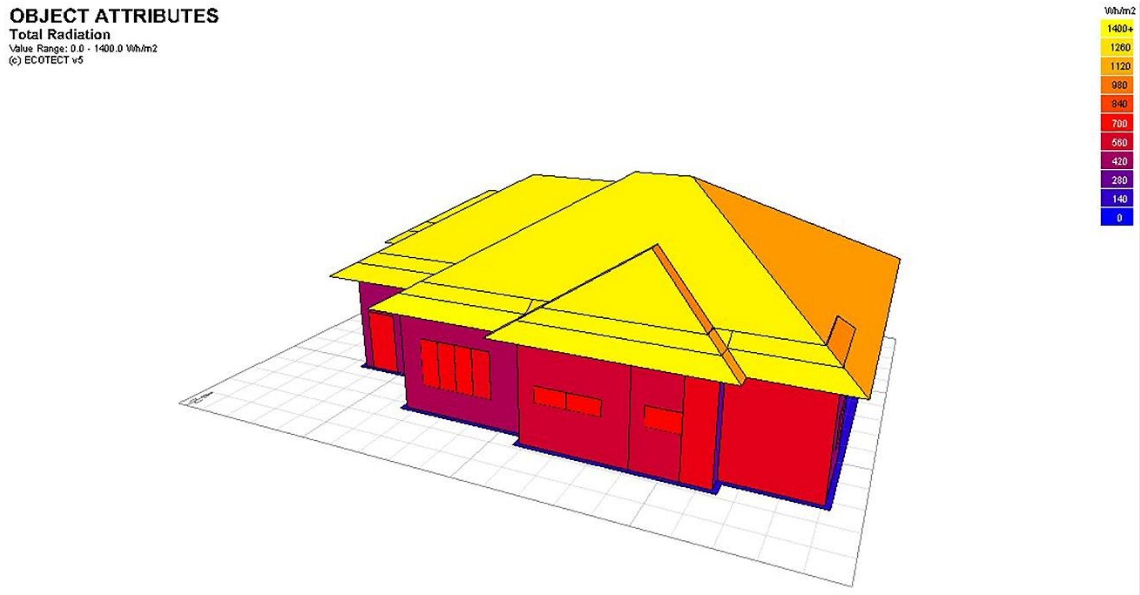


Figure 9.Solar energy absorption by surfaces of case study house.

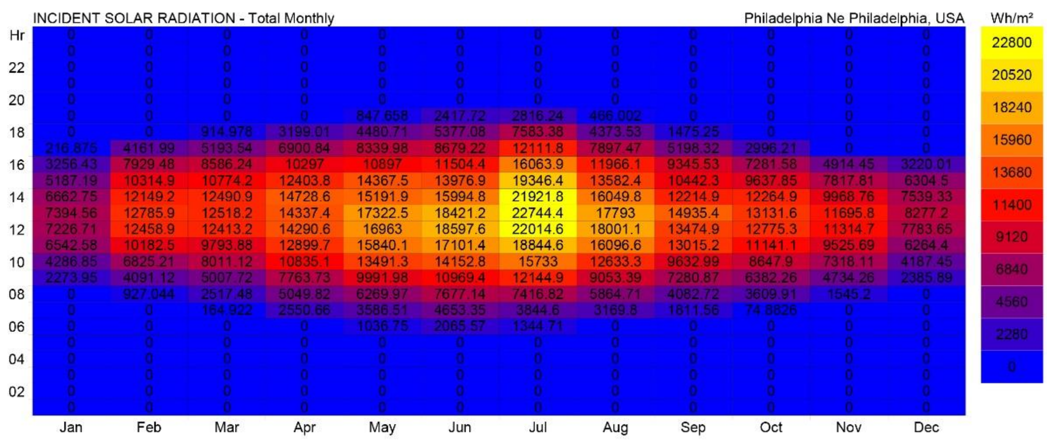


Figure 10. Total annual average irradiation (incident solar radiation) of the case study house.

From simulation results, a PV power system can be mounted on the roof of the case study house as heat absorbers and cost-effective solutions to minimize energy demand. This approach can be considered in support of strategic goals of designing house with net zero energy. The balance between energy consumption and production of renewable is a very important factor to determine the optimum solutions of ZEHs. As mentioned before, the methodology for this study required establishment of the relationship between these factors. In this respect, Equation (2) was used for calculation of the solar energy output of the PV power system as follows:

E = 225.492 m^2 (Roof area) × 25% ×1245.261 (kWh/m^2) ×0.75=52,600 kWh/ yr

According to this calculation, the annual solar energy output of the PV system is higher than the existing total annual cooling and heating energy consumption (50,920 (kWh)), which reached after application of PCM. This performance reflects the design of zero energy case study house presented in this paper and its potential can be tailored to the unique interoperability opportunities between energy analysis and design phases of a BIM-based tool.

In case of ZEHs, it is important to develop calculation methodologies for incident solar radiation, which is an important consideration in making energy efficiency decisions. Understanding the significance of incident solar radiation will help designers achieve thermal mass, and orient buildings to capitalize on the benefits of the sun's energy. In this context, it is important to provide an initial indication of the optimal orientation with respect to the sun. A simulation was performed in Ecotect to confirm the orientation with the lowest energy requirement for the case study house (Figure 11). This process can also be used to specify overheated and underheated months.

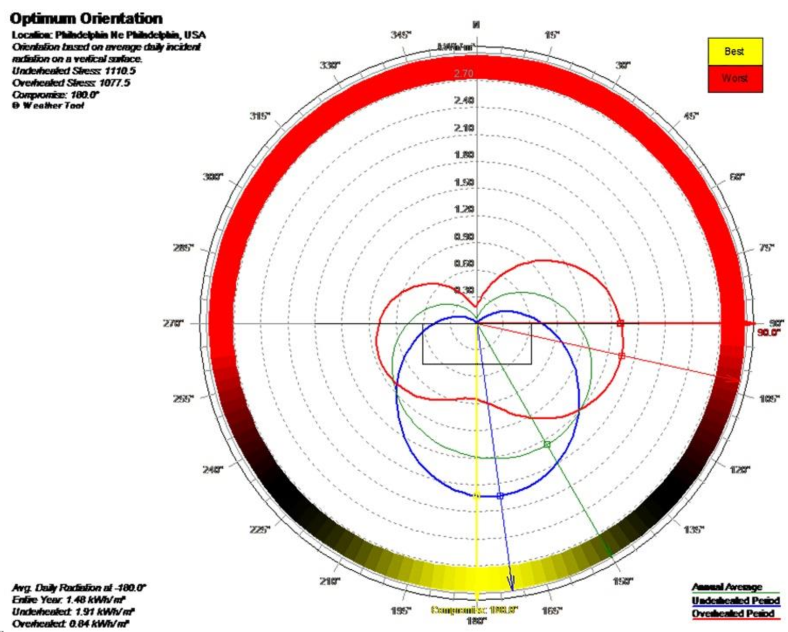


Figure 11.Optimum orientation for specified overheated and under-heated months.

According to the results of the above-mentioned processes, it was found that the BIM-based model can create an accurate thinking of the methods for simulating energy consumption and characterizing building data. For example, BIM-based model was shown to be interoperable with BPS tools to determine energy-relevant characteristics of the building envelope that play a key role in reaching ZEHs.

CONCLUSIONS

The study presented here illustrated how the BIM technology can be capable of designing and addressing a ZEH, through application of a type of PCM and calculation of annual heating and cooling energy demands. This study considered the feasibility of the proposed methodology according to cost-effective changes and the economic benefits of BIM.
In this study, BIM was used through Ecotect and Opaque software to determine effective energy-efficient strategies during early stages of the design process. The study revealed that

a number of building energy technologies such as BIM and BPS tools can be used in an integrated manner for achieving a net-zero energy level. The paper also presented a literature review with a focus on PCMs applications in designing ZEHs. It is also concluded that for ZEHs to meet relevant code requirements, potentials of achieving considerable energy savings and the efficient use of renewable energy source such as solar are highly important. The central information platform in BIM system can enable architects and designers to share knowledge for development of ZEHs. Considering the interoperability of the BIM system with BPS tools was able to make considerable progress toward analyzing and upgrading an existing residential house to net-zero level.

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Software Tool for Automation in Building Energy Simulation Using Building Information Modeling (BIM)

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Abstract

Conventional building energy modeling (BEM) process for residential buildings could be time-consuming, error-prone, and requires expertise. Required parameters for energy simulation including building geometry need to be modeled in a BEM graphical user interface (GUI). Emerging capabilities such as Building Information Modeling (BIM) could contribute to automating this process. All the required information could be defined in a BIM file and used directly for energy simulation to make the whole process faster and less error-prone. This paper explains a software tool developed for automating residential building energy simulation using BIM. In addition, this tool could also contribute to providing detailed information concerning heat transfer through building envelope components such as walls, windows, roof, and floors for monitoring purposes. Tools used to develop this software capability include the modified source code of OpenStudio and EnergyPlus. A case study is used to validate the outputs of the tool using Revit to generate a BIM file, which is later converted to an Input Data File (IDF) file that includes all the required data for energy simulation to be used in modified EnergyPlus. Results are compared to the outputs from existing energy simulation tools, which will show that this tool is capable of performing automated energy simulation.

Keywords: Building Energy Modeling, Building Information Modeling, EnergyPlus, OpenStudio

Introduction

Energy modeling of buildings can help identify the extent of energy consumption and different building attributes with highest contribution to energy demand. Multiple researchers have worked on improving BEM process in terms of speed and accuracy using different measures. The process in conventional BEM computer tools consists of developing a digital model of building's geometry and other characteristics affecting the energy consumption such as types of heating, ventilation, and air-conditioning (HVAC) systems, lighting system, load schedules, appliances, exterior temperature, and interior temperature defined by thermostat temperature setpoint. Such a process is performed by developing a model in a graphical user interface (GUI). For instance, DesignBuilder, SketchUp, and BEopt benefit from a GUI, which enables the users to model the aforementioned components. Subsequently, such data will be translated to an "energy simulation engine", which is an integral component in a BEM computer tool. EnergyPlus and DOE2 are among the most prevalent energy simulation engines working with other energy modeling GUIs [1].

These energy models are normally developed after or during the structural design of buildings, which means that all the information related to buildings are already available and even modeled in computers using other computer-aided design (CAD) tools such as AutoCAD, Rhino, and Revit. Therefore, all this information should be reentered in an energy simulation model.

Accordingly, there are several aspects in energy modeling and simulation process that can be improved with regards to the speed of the process by minimizing the reentry of data throughout the design and modeling process of buildings, and accuracy by minimizing the risk of human errors in data input process. An energy modeling process that is geared toward automated process would be of higher interest. There are emerging techniques such as building information modeling (BIM) and CAD models using 3D laser scanners, which automate and pace up the modeling process. While 3D laser scanners can only capture the information related to the geometry of objects, BIM tools can transfer almost all the attributes related to buildings specially those, which are required for building energy modeling and simulation.

While some energy simulation tools such as Green Building Studio (GBS) developed by AutoDesk use BIM features, there are also other BEM tools such as OpenStudio that are capable of importing BIM models using its GUI. Two of the most prevalent BIM schemas used by these tools are industry foundation classes (IFC) and Green Building XML (gbXML). Although these file schemas are capable of transferring almost all the required information with regards to energy modeling, it should be noted that some pieces of information might be missing or modified through the translating process between different BIM and BEM tools [2, 3, 4, 5, 6, 7].

This paper introduces a new software tool developed to perform energy modeling using BIM and provides granular outputs concerning heat transfer through building envelope components. The next section explains how the aforementioned shortcomings are solved using this tool, followed subsequently by showing the results of validation of this tool and the implications of the results.

Methodology

In order to overcome the issues and shortcomings related to the energy modeling process it was decided to implement BIM into the BEM process. While this idea is not new, there are several challenges for such an implementation as listed below.

- Most of the existing BIM and BEM tools are not open-source, which makes it hard to obtain desirable outputs other than what is available in existing BEM tools.
- BIM file schema might not be capable of transferring all the required information required for energy simulation.
- Data transfer concerning certain building information might not be performed flawless and some data might be lost.
- BIM tools and energy modeling tools might not be compatible and data translation might not be performed in a solid and stable way causing errors.

This tool is developed using the source codes of EnergyPlus and OpenStudio and it is compatible with gbXML file schema converting it to input data file (IDF) for energy analysis. The overview of this tool is illustrated in Figure 1.

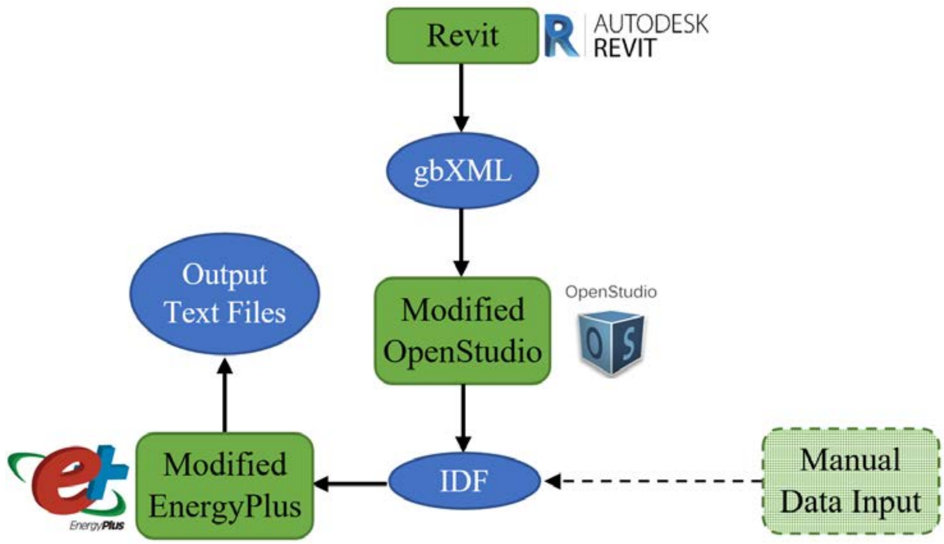

Figure 1. Overview of developed computer tool for automated energy simulation

Before explaining the methodology, which was adopted to overcome the aforementioned challenges, it is necessary to describe the components in this software tool in more details. These components can be listed as follow:

1) Revit is used as the BIM tool to export a building model, which includes all the required information, to a gbXML file.
2) Corrective tool is developed using Python, which gets the gbXML file and corrects certain issues related to interoperability difficulties.
3) A gbXML-to-IDF translator is developed by using existing routines in OpenStudio source code.
4) Modification is made to EnergyPlus using C++, which receives the IDF file and saves the granular data on heat transfer through walls, windows, doors, and floors into separate text files.

In this context, it can be observed that the open-source tools such as OpenStudio and EnergyPlus are used in developing this tool in order to be able to make the necessary changes throughout the process and also to be able to obtain the required data, which are not instantly available as EnergyPlus regular outputs.

In order to overcome the issues with BIM file schema in terms of including all the required data for energy modeling, it was decided to use gbXML file schema. This file schema is specifically designed for energy simulation and it is capable of defining and transferring all the required data including the geometry, schedules, HVAC properties, types of lighting system, appliances, and material thermal properties. Similar issues and limits in data transfer using certain BIM file schemas are also addressed by other researchers [8, 9, 10, 11].

Another challenge is about missing certain data through the data transfer process between different computer tools. For example, when a model is developed in Revit and exported to a gbXML file, some data related to schedules and HVAC properties might be lost. As a result, some of these data was manually added to the IDF file, as it is shown in
Figure 1. Such data include the temperature setpoint for thermostats and schedules related to HVAC, lighting and appliances.

The next challenge was incompatibility between different tools. For example, the gbXML file generated by Revit cannot be directly used in gbXML-to-IDF translator (modified OpenStudio) due to certain issues explained in more details in next section. Therefore, it was necessary to develop a corrective tool using Python, which receives the gbXML file and rectify those issues before being used as an input for gbXML-to-IDF translator.

Eventually, a modified EnergyPlus source code is used to receive the IDF file and a weather file to perform the energy simulation. The source code is modified in order to make the tool capable of generating text files containing detailed heat transfer through every single wall, window, door, and floor. Such level of granularity is not instantly available in BEM tools through a fast and accurate process.

Results and Discussion

To assess the functionality of this tool, a simple one-story building is first modeled in Revit. All the required information with regards to the HVAC system, schedules, material properties, and geometry were defined. Figure 2 shows the layout of this building.

The model was exported as a gbXML file. One of the interoperability issues between this file and gbXML-to-IDF translator (modified OpenStudio) was repeated lines of information and also missing data concerning material properties for doors, both causing errors. The corrective tool developed using Python managed to successfully rectify these issues by removing the extra lines and also adding the material properties related to doors.

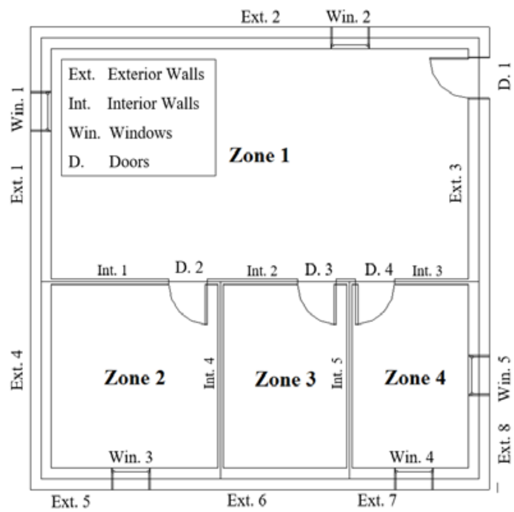

Figure 2. Overview of developed computer tool for automated energy simulation

Afterward, the gbXML-to-IDF translator (modified OpenStudio) managed to translate the corrected gbXML file into an IDF file and the missing information related to the HVAC, schedules, and thermostat setpoint temperatures were added manually.

The weather data for Boston was used to perform the energy simulation for this building and the outputs were successfully obtained and automatically saved in separate text files containing granular data for heat transfer through every single building envelope components. To verify the outputs of this tool, these data were also obtained through a different process. Accordingly, EnergyPlus advanced outputs were calculated, a task that is a time-consuming process requiring software-related skills. The outputs of these two methods for thermal zone #1 are shown in Table 1. It can be observed that the outputs of the developed tool are failrly close to those obtained by the other method and within 2% accuracy, which shows the functionality of this tool.

Table 1. Comparison between the heat transfer through every single component obtained from the developed tool and EnergyPlus advance outputs for data validation purposes

Building Envelope Components		Advanced outputs of EnergyPlus (GJ)		Direct outputs of the developed tool (GJ)	
		Gain	Loss	Gain	Loss
Zone 1	Ext. 1		-0.617		-0.629
	Ext. 2		-1.469		-1.498
	Ext. 3		-0.585		-0.595
	Int. 1		±0.024		±0.024
	Int. 2		±0.015		±0.015
	Int. 3		±0.017		±0.017
	Flr. 1		-0.592		-0.609
	Rf. 1		-1.444		-1.470
	Win. 1	2.033	-0.934	2.033	-0.934
	Win. 2	0.766	-0.958	0.766	-0.958
	D. 1		-1.220		-1.243

Summary and Conclusions

In order to improve the BEM tools and the modeling process, a new tool was developed using BIM. Application of such tools can improve the accuracy and speed of energy modeling by minimizing the human interaction and eliminating the need for reentering data. Moreover, the granular data on heat transfer through every single component such as walls, windows, doors, and floors can help in having a more energy efficient building design and energy retrofit process by identifying the components with higher contribution to energy loss.

The developed tool uses gbXML file is its input and rectify the file transfer issues between different tools by adopting a corrective tool developed using Python language. The corrected file will be used as input for the gbXML-to-IDF translator, which is developed by using the existing routines in OpenStudio source codes. The produced IDF file is then fed to the modified EnergyPlus alongside the proper weather file. The modified EnergyPlus source code is capable of performing the energy simulation and report the heat transfer through every single wall, window, floor, and door inside the building. Based on the results of this study, the following concluding remarks can be made:

- Further studies need to be done to identify the challenges and issues related to the interoperability issues between different BIM and BEM tools.

- The study show underlines the need to develop middle-ware tools, similar to what is developed in this paper using Python.
- These middle-ware tools could be focused on different types of information such as HVAC properties and schedules.
- Open-source software tools such as EnergyPlus and OpenStudio seem to perform well for such processes.
- The study shows that visualizing the granular data similar to what is presented in this paper through addition to existing BEM tools can be beneficial during the design phase or energy retrofit process of buildings.

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Impact of Positioning Phase Change Materials (PCMs) within Building Enclosures on Thermal Performance

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ABSTRACT

Utilization of phase change materials (PCMs) in building enclosures as thermal energy storage systems (TES) has become a re-appearing topic within the research community in recent years. PCMs represent an innovative solution that can contribute to the improvement of energy efficiency and thermal performance of buildings. This paper aims to present results of experimental investigations regarding the effectiveness and differences of PCM positioning within building enclosures in terms of energy performance and thermal comfort. The experiments are conducted in a laboratory setting, more specifically in an environmental test apparatus, that allows for comparative testing of interior thermal and hygrothermal performance under different exterior climate scenarios. The paper discusses the experimental setup, the employed analysis methods, and findings of effects for different PCM positions in exterior wall configurations. It explores the observed differences and discusses potential opportunities that exist in regards to reducing overall thermal losses in enclosures and improving thermal comfort in interior spaces.

INTRODUCTION AND BACKGROUND

Phase change materials (PCM) are latent heat storage materials with a high heat of fusion that melt and solidify at a certain temperature (Kenfack and Bauer 2014). They have the ability to store and release high amounts of heat and energy for a required temperature range with lower temperature differences during phase transfer (Thomas et al. 2015). The temperature remains almost constant when these materials store and release thermal energy (Nkwetta and Haghighat 2014) and they can be used as a temperature controller (Cabeza and Mehling 2007). Typically, the heat storage capacity per unit volume of PCMs is much higher than the sensible heat storing capacity of materials (Williams 2009).

There is a worldwide focus on energy conservation and PCMs are expected to play an essential role in the near future. With PCMs features and products improvement for building applications, PCMs are expected to create new opportunities in the PCM market as well as their utilization as building materials (Mordor Intelligence LLP 2016).

PCMs have been studied for several years and considered for building applications to take benefit of the latent heat capabilities and high thermal storage densities. The characteristics of PCMs make them suitable to be used in buildings for energy savings, space/size saving, reducing building load, and reducing peaks in demand period (Kośny 2015). A PCM's main advantages come into play when they are used as building materials where spaces require more thermal storage capacity against changing boundary conditions that cannot be utilized through thermal mass layers within a building enclosure (Abuzaid and Reichard 2016). PCMs have been tested in various application as a thermal mass components in buildings, and most studies have found that PCMs enhance thermal performance in buildings (Kosny et al. 2007).

However, each building material has its advantages and limitations and new construction materials have emerged in the market. The selection of PCMs has to fit the application requirements (Gracia and Cabeza 2015). Moreover, any practical PCMs require at least: a proper melting point in the desired temperature range and high heat of fusion per unit mass and volume (Humphries and Griggs 1977), along with a suitable heat exchange surface and a suitable container compatible with the PCM (Sharma et al. 2009). In addition, there are a number of challenges and limitations of utilizing PCMs in building applications, such as: material compatibility, loss of phase-change capability, cost and availability, and health/safety and disposal (Richard 2013). These challenges and limitations generally depend on PCM type and properties and ultimately will have different impact at different positions within a construction assembly. While the motivation of utilizing PCMs in building construction has been discussed in aspects such as material properties and space applications and summarized by others (Pomianowski et al. 2013), the placement and effectiveness of products based on their positioning still needs more investigation.

PROBLEM STATEMENT

Air conditioning energy consumption in different seasons represents a challenge in many areas with hot and/or cold climates. Heating and cooling loads represent the largest part of energy consumption in buildings. According to the International Energy Agency (IEA), in most countries the average energy consumed by buildings represents 32% of all-inclusive worldwide energy consumption and with approximately 40% of the primary energy consumption (IEA 2015). Similarly, creating a thermally comfortable environment for occupants of buildings is highly desirable and maintaining indoor temperatures within the comfort zone is required in most occupied buildings. Saving energy and providing thermal comfort for building occupants are very important aspects to be considered by building designers, architects, engineers, and contractors, and these goals could be supported by utilizing PCM within building enclosure.

PCMs are still not commonly used as thermal storage in building construction as several challenges and questions exist regarding the application of PCMs as building materials within building enclosures. One of the questions is a lack of understanding the impact of PCM positioning within the building enclosure as a remaining challenge.

This paper assesses the effects of utilizing PCM in building enclosures and their benefits towards thermal performance by comparing interior versus exterior installation positions.

EXPERIMENTAL SETUP

To investigate the impact of using PCM on energy reduction and improving thermal comfort, laboratory experiments have been conducted. The aim of the laboratory experiments was to evaluate the implementation of PCMs in different positions by carrying out a comparative study. The tests have been conducted in an indoor environment to enable testing of PCMs under controlled climate conditions, while focusing on different positions for fixed periods of time. Placing the tests in an indoor laboratory allows for monitoring and controlling the experiment's environmental conditions and parameters as well as for moderating outside influences that would otherwise affect test results. The experiments were conducted in the same laboratory space, utilizing the same material properties, dimensions, equipment, and temperature ranges to study the differences of results among different positions (exterior and interior sides of a wall cavity) of a PCM in a building enclosure and compare results with a wall without utilization of PCMs. These experiments were conducted under controlled conditions for a set running time for heating and cooling periods of 12 hours each. The evaluation included monitoring how PCMs overall behave in different temperature ranges and positions, as well as their ability to reduce temperature fluctuations across wall components and influence on peak-load shifting.

For this test, a 5.0 cu ft chest-freezer was used to facilitate the cold exterior temperatures and three light bulbs (40 watts each) to create the hot exterior temperatures within the chest for comparison. Figure 1 shows the experimental setup of the study and illustrates how equipment and devices have been connected. Wireless HOBO ZW data nodes and sensors were used to measure and log inside and outside temperatures for both surfaces, interior (room-side) and exterior (chest-side) air temperatures, and several temperatures across the different layers of the wall components. The data loggers were configured to collect data at 1-minute intervals. For controlling the time of heating and cooling periods, wirelessly programmable WEMO switch devices were used to program and monitor the On/Off timing cycles. To maintain the periods of predefined "exterior" temperatures within the chest chamber, this study used digital temperature controllers (WILLHI WH 1436) to control set point temperatures of heating and cooling for each scenario. Figure 2 shows the control panel utilized in the study and devices that have been used in the experiments.

To record temperatures, eight thermocouple sensors were used (type TMC-HD and TMC-HC). Three sensors were used to measure temperatures with relative humidity (type RHPCB) to capture exterior and interior climate, as well as one cavity position. To capture the changes in the PCM phase a temperature sensor was placed on each side of the PCM. Figure 3 illustrates the test apparatus with interior and exterior setup configurations as well as the position of sensors utilized in the study.

Figure 1 Experimental setup with data logger and computer

a) b) c) d)

Figure 2 a) Control panel assembly; b) data logger node and receiver; c) timer modules; and d) temperature controller

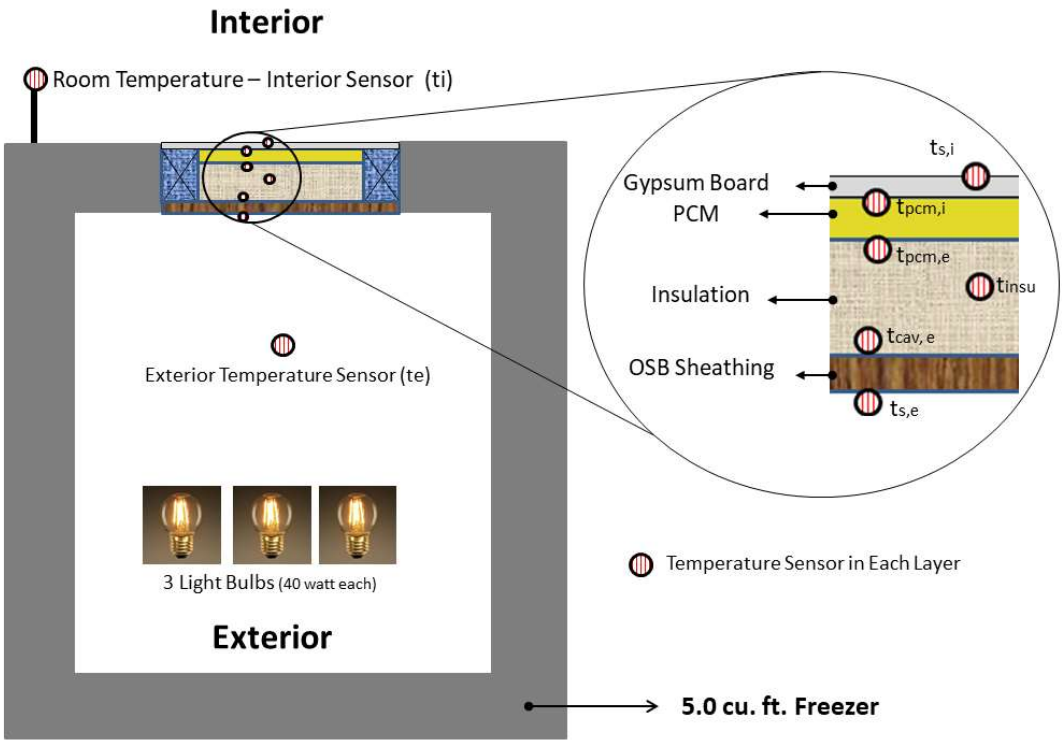


Figure 3 Schematic diagram of the experimental setup and sensor positions

In total, nine sensors were used throughout the experiments. Table [1] shows the taxonomy used for these sensors and their correlating positions.

Table [1] Sensors and Positions

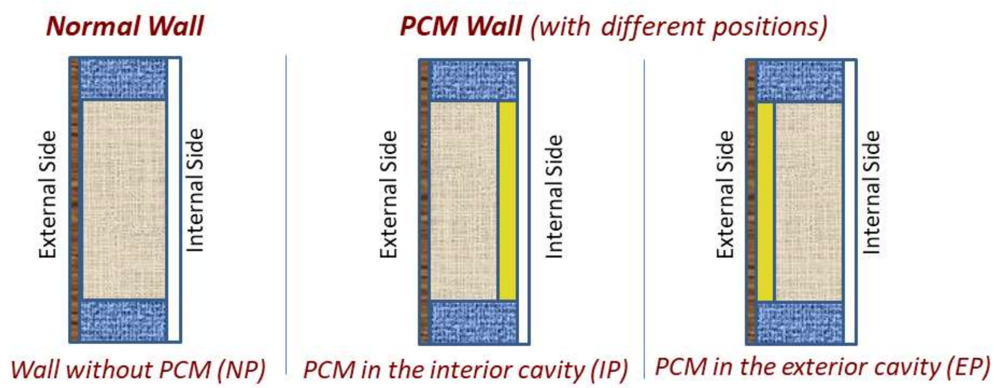
Sensor Name	Position
t_i	Temperature of interior
$t_{s,i}$	Temperature of surface (interior)
$t_{cav,i}$	Temperature of cavity (interior)
$t_{pcm,i}$	Temperature of PCM (interior side)
$t_{pcm,e}$	Temperature of PCM (exterior side)
t_{insu}	Temperature of insulation
$t_{cav,e}$	Temperature of cavity (exterior)
$t_{s,e}$	Temperature of surface (exterior)
t_e	Temperature of exterior

Description of Specimens:

The studied specimens were based on a common cavity filled stud wall, which was then expanded with different PCM configurations. In total, three specimens were used in the laboratory experiments:

1. A specimen without any PCM layer (NP),
2. A specimen with a PCM layer at the exterior side of the cavity (EP), and
3. A specimen with a PCM layer at the interior side of the cavity (IP).

The wall specimens were mounted into frames made of extruded polystyrene (XPS) foam and contained gypsum board for the internal sheathing layer, a cellulose insulation layer, the PCM (Bio-based PCM mat), and an oriented strand board (OSB) for the external sheathing layer (Figure 4 . All specimens had the same dimensions of 40 cm x 40 cm with a total thickness of 15 cm.



	Wall without PCM (NP)		Wall with PCM (IP)		Wall with PCM (EP)	
Layers	Material	Thickness	Material	Thickness	Material	Thickness
	Internal surface	--	Internal surface	--	Internal surface	--
	Gypsum board	1 cm	Gypsum board	1 cm	Gypsum board	1 cm
	Insulation	12 cm	PCM	1.5 cm	Insulation	10.5 cm
			Insulation	10.5 cm	PCM	1.5 cm
	OSB sheathing	2 cm	OSB sheathing	2 cm	OSB sheathing	2 cm
	External surface	--	External surface	--	External surface	--

Figure 4 Sections of wall specimens and utilized materials

The utilized PCMs had the following properties and dimensions as shown in Table [2].

Table [2] PCM`s Properties

Item	Description / Value
Manufacturer	Phase Change Energy Solutions – (USA- Asheboro, NC)
Material Name	ENRG Blanket Q23/M27 - Bio-based PCM mat - Solid/Liquid phases
Filling	Natural vegetable oils and proprietary blend of emulsifiers, gelling agents, fatty acids, and their derivatives
Encapsulation (thickness)	15 mm (Multilayer white polyfilm)
Melting Point	23°C
Latent Heat Storage Capacity	175-250 J/g
Weight	2.49 kg/m²

Experimental Limitations:

This study is limited to thermal aspects in building enclosures, specifically in an external wall. Outdoor temperatures were controlled at fixed temperature differentials for exactly timed hot and cold periods. Phase change processes were limited to solid-liquid transformations as the utilized PCM was a bio-based matt with a melting point of 23 °C and the temperature differential never exceeded more than 25 °C.

Detailed assessments of HVAC loads, heat flux, or overall energy consumptions, variations of design materials, or impact of relative humidity were not addressed. The experiments were focusing on temperature changes only and the effects of the PCM during heating and cooling in different positions within the building enclosure.

A future study with test cycles replicating real climate data and measurements of heat flux along with energy consumption will provide a broader understanding of PCMs' impact on the thermal performance of the building enclosure.

METHODOLOGY

Experimental Procedure

The objective of this study was to experimentally evaluate the impact of different positions of a PCM within the building enclosure on thermal performance. The study employed the same experiment with three different specimens to assess the impact of the different PCM positions: 1) a wall with a PCM at exterior side of the wall cavity (labeled as EP for *exterior PCM*), 2) a wall with a PCM at the interior side of the wall cavity (IP for *interior PCM*), and 3) a wall without PCM application (NP for *no PCM*). Each experiment was conducted for 48 hours with two cycles of 12 hours of cooling and 12 hours of heating each. Each experiment started with a cold period by turning on the freezer for 12 hours to make sure that the PCM completely reached the solidifying phase. Then, the warm phase was initiated by turning on three light bulbs within the chest freezer to reach and maintain the hot climate setpoint for 12 hours alternately. The 12-hour cycle was selected to achieve complete melting and freezing phases of the PCM through each cycle.

The controlled setpoint temperatures for the exterior climate were based on the maintained interior laboratory room temperature. Exterior temperatures were held at 45 °C for the hot periods and at 0 °C for the cold climate periods, while the set point of the room temperature was kept between 22-23 °C, which represents the range of the melting point of the utilized PCM. The recorded indoor temperatures across all experiments showed less than 2 °C of fluctuation. Figure 5 shows an overlay of all recorded interior and exterior temperatures across all the different 48-hours experiment cycles. Relative humidity was monitored and recorded, but not considered for the analysis of this study.

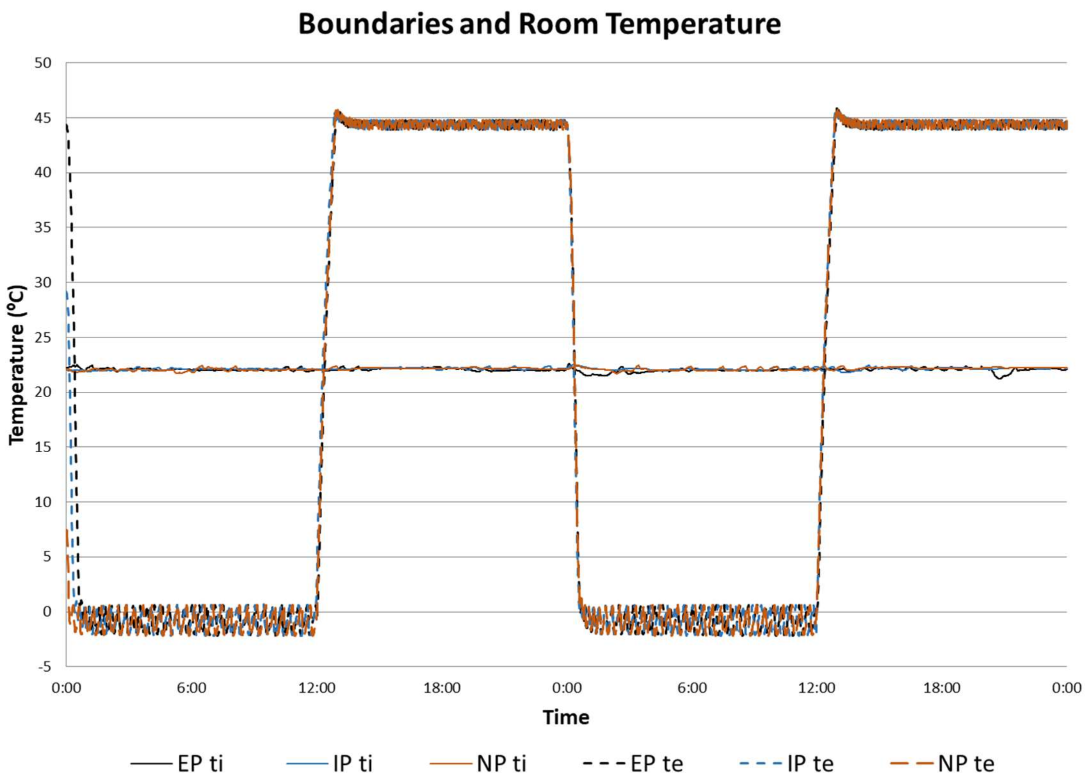


Figure 5 Recorded interior and exterior temperatures during cycles

Analysis Methods

The analysis of the experimental results focused on the impact of PCMs in different positions in terms of thermal performance and peak-load shifting during heating and cooling times. The study therefore focused on three stages of analyses:

Differential Result Patterns of PCMs in different Positions

In a first analysis stage, a quantitative comparison of temperatures over time was carried out to identify areas of difference for further investigation and discussion. The experimental results were cleaned and then presented in graphical form. A comparative discussion of temperature data during the hot and cold phases for each PCM position was conducted.

Analysis of impact of PCM positioning on thermal comfort

The second analysis stage focused on evaluating the impact of PCM position on thermal comfort by observed and analyzing differences in surface temperatures. As surface temperatures are critical indicators for thermal human comfort, this analysis developed a metric termed *Comfort Degree Minutes* that integrates the difference between room temperature set points and recorded surface temperatures against a temperature threshold (replicating the thermostat reaction range) for each PCM position.

$$CDM_{th} = \sum \left| t_{s,i} - t_{th} \right| \cdot \Delta m \quad for\ all \quad t_{s,i} \geq t_{th}$$

where

$t_{s,i}$ … the interior surface temperature in °C
t_{th} … the reference (threshold) temperature in °C
Δm … the time interval in minutes

Analysis of impact of PCM positioning on peak load shifting

The third analysis stage investigated the impact of PCM positions on peak load shifting. This analysis was based on the comparison of the crossover points of temperatures when changing from cold to warm phases and vice versa in the different experimental cycles. The recorded time was considered an indicator of the amount of peak-hour shift that could be achieved for a given assembly. The underlying assumption is that any capability of capturing internal thermal loads of heating or cooling cycles and shifting them to off-peak periods could contribute to energy savings, either through short-term changes in climatic boundary conditions at the shifted time (e.g. use of economizers), or alternative grid demand and generation cost. The analysis used a graphical assessment method through scaled result diagrams to evaluate the ability of latent heat storage in different positions to shift peak loads and discuss notable savings potentials.

RESULTS AND DISCUSSION

Overall, the results of the experiments confirmed the latent changes through delayed changes of temperatures in different positions of the specimen profiles of specimen layers that were to be expected when utilizing PCMs.

Differential Result Analysis of PCMs in Different Positions

There were several observation made in the first analysis stage that utilized graphical methods for comparison of recorded results. A graphic overlay of all experiments confirmed that the results showed reasonable repeatability of the PCM behavior in each position during the various solidifying and melting phases with consistent performance in each cycle. Similarly, the PCM specimen showed the same behavior under repeated tests.

In terms of temperature differences over time, it was observed that when the PCM was placed on the exterior side of the cavity (EP), the temperature differences between interior ($t_{pcm,i}$) and exterior ($t_{pcm,e}$) side of the PCM were more pronounced than when placed on the interior side (IP) of the cavity. For EP experiments, the melting and freezing periods are clearly visible where the temperature difference widens and becomes larger than the standard proportional difference of the material's thermal resistance.

Furthermore, when the PCM was utilized in the exterior position (EP) of the wall, it reacted faster, but it did not reach its steady state in either cycle. In contrast, when the PCM was utilized in the interior position (IP), it reached a steady state condition in each phase after 4-6 hours. In both positions, the PCM activated its thermal storage capacity, but its performance during the freezing phase was slightly better than its performance during the melting cycle (Figure 6).

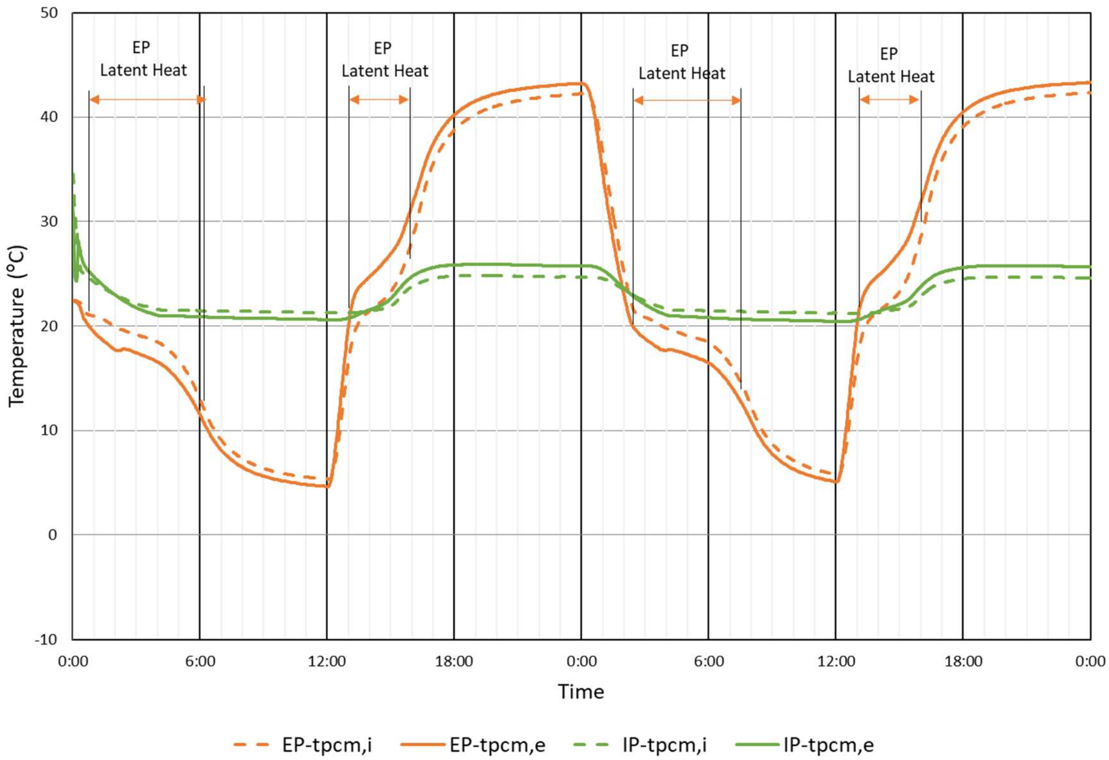


Figure 6 Comparison of temperatures showing PCM activation during exterior (EP) and interior (IP) cavity placement

For the warm exterior climate periods, an effect of increased heat transfer at the exterior surfaces was detected, where surface temperatures exceeded the recorded exterior air temperatures that were controlled by the thermal sensors of the switching device. The increased heat transfer effect can be attributed to an increased radiant heat exchange through the utilization of light bulbs as a heating source, which in turn has an impact on temperature of the external surface ($t_{s,e}$) of the specimen. This effect was observed across all experiments. More specifically, the effect accrued over time, as more and more heat is absorbed through radiation, bypassing the conduction and convective exchange through air.

There are differences between the scenarios at which time the $t_{s,e}$ exceeded the exterior air temperature t_e. Notably, this delay was most pronounced (4 hours) for the experiment when the PCM was placed in the exterior position of the cavity (EP). For the interior position (IP), the effect of radiant heat exchange made $t_{s,e}$ exceed t_e within 2 hours. Figure 7 shows the effect of radiant heat exchange on the external surface temperature during heating cycles.

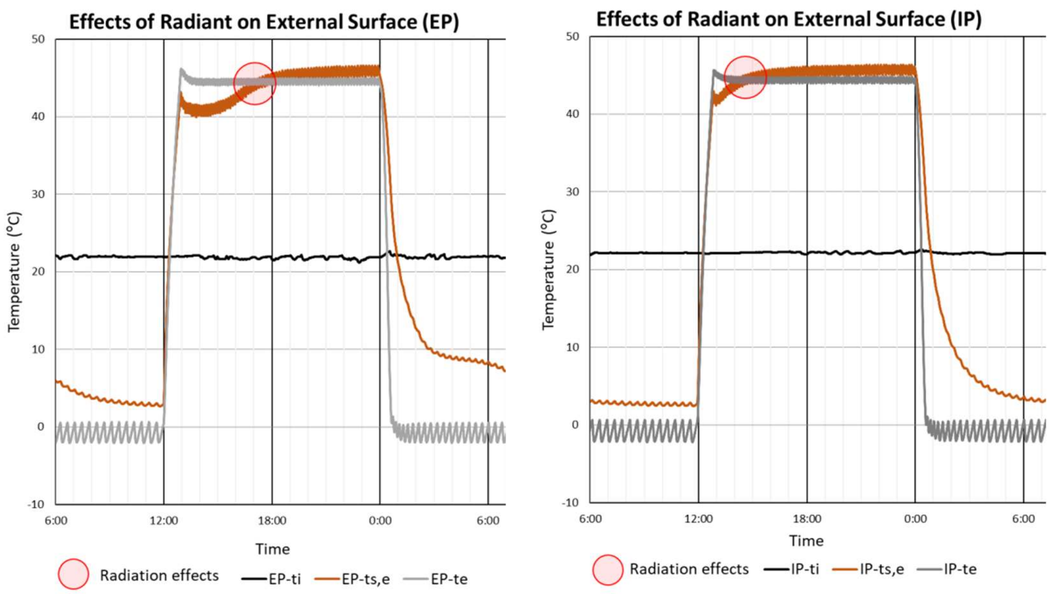


Figure 7 Effect of the radiant heat exchange observed at external surface

Analysis of impact of PCM positioning on thermal comfort

This phase of the study analyzed the measured temperatures of the experiments in terms of their effect on thermal comfort. For this evaluation, calibrated and measured interior surface temperatures were utilized as contributing metrics towards broader comfort considerations. Figure 8 shows a comparative distribution of the measured surface temperatures of all specimen types across the entire experimental cycle. However, the first cold and hot temperature cycles are less practical for evaluation but are rather considered as a "swing-in" phase as a starting vector of boundary conditions. For detailed analytical evaluations, only the second cold and hot temperature phases were evaluated (hours 24-48).

The impact on comfort was assessed through calculating a specific metric that was developed for this study and termed "comfort degree minutes" (CDM), as it captures temperature differences between interior surface temperature ($t_{s,i}$) and its offset from the interior setpoint or threshold temperature. Figure 9 illustrates this method graphically, where the area between $t_{s,i}$ and the cut-off threshold temperature represents the CDM value.

The comfort degree minutes for the different specimen were calculated as follows:

Table [3] Comfort Degree Heating Minutes (CDM-H) when switching to hot climate

	EP	IP	NP
CDM-H-22.5	281	343	664
CDM-H-23.0	46	112	359

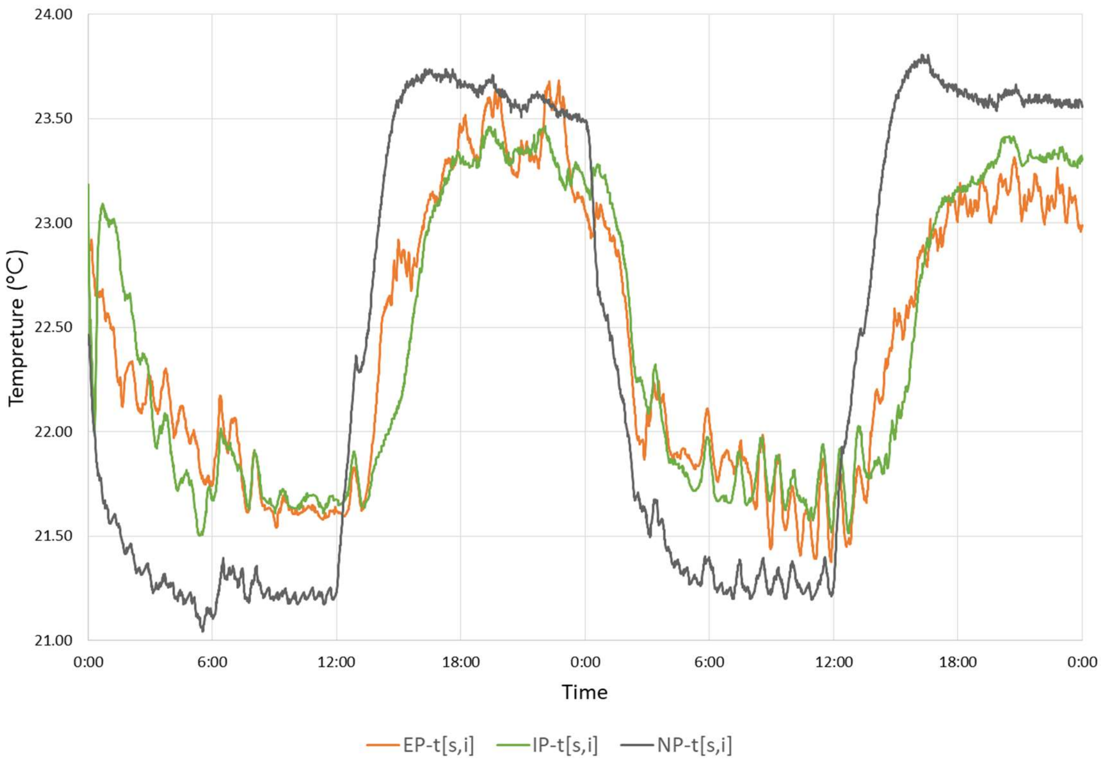


Figure 8 Interior surface temperatures ts,i for the different wall specimens

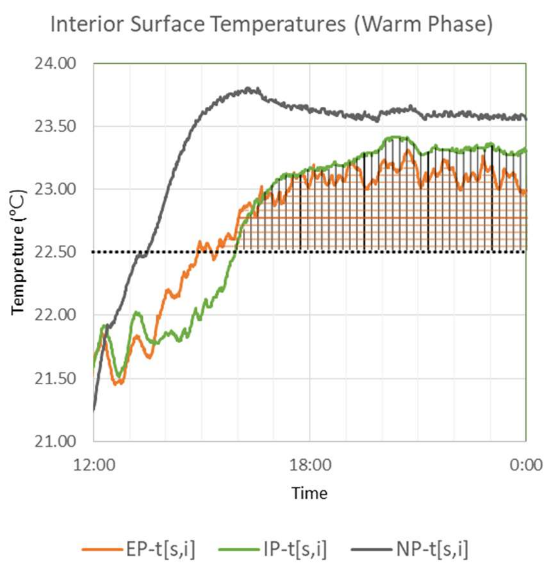


Figure 9 Visualization of assessment of Comfort Degree Minutes CDM-22.5

Table [4] Comfort Degree Cooling Minutes (CDM-C) when switching to cold climate

	EP	IP	NP
CDM-C-22.5	394	413	852
CDM-C-22.0	116	117	383

The results of these assessments illustrate that specimen EP shows the smallest number of CDMs followed by specimen IP when moving from a cold to the hot climate. When undergoing the reverse change moving from the hot to the cold exterior phase, no significant difference is observed between the two PCM positions EP and IP, while again a notable difference can be observed for the specimen without PCM (NP). These results indicate a slight advantage for PCMs in the exterior position of the cavity, but further tests will have to be conducted to verify this observation in connection with other material combinations.

Analysis of impact of PCM positioning on peak load shifting

PCMs are known to help deflect or at least defer cooling or heating demand over a certain time while actively changing their phase. This effect shows well throughout the experiments of this study. To compare the different positions of PCM placement in terms of contributing to any load shifting effect, a graphical analysis was utilized to measure the achievable lag during hot and cold periods.

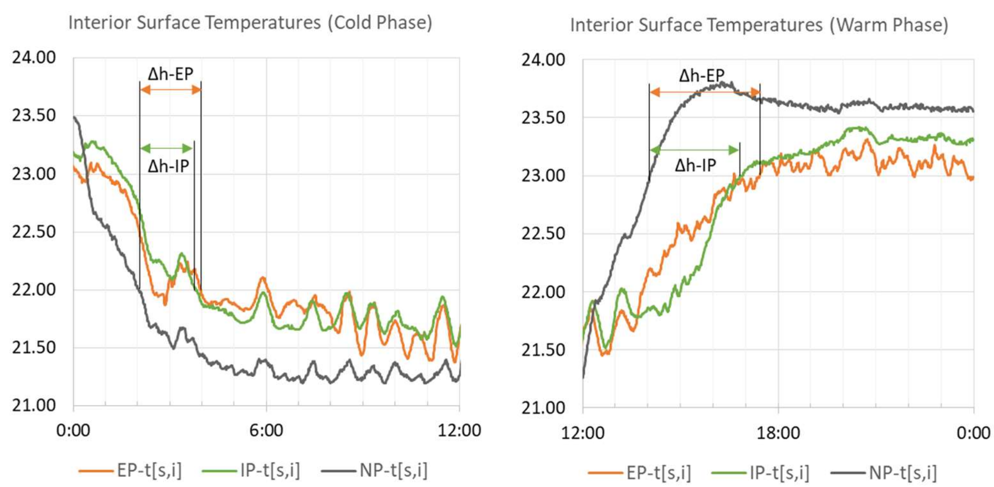


Figure 10 Interior surface temperatures ts,i for the different wall specimen

Both positions showed significant lag times when shifting from the cold to the warm exterior climate periods. However, the EP specimen achieved a slightly bigger lag of more than 3 hours in these experiments, while the IP position only achieved around 2.5 hours. Interestingly enough, when switching to cold periods the effect becomes less visible and the differences are less pronounced between the two PCM positions. In both scenarios, it can be observed how the temperatures of the interior surface ($t_{s,i}$) start merging again as the phase change effect wanes off.

Obviously, the amount of time lag that can be achieved is in direct relation to the amount of PCM utilized, which can be altered by design if needed. The purpose of this study was only to investigate eventual differences between positioning the PCM. From the preliminary results obtained in this study, it seems that the exterior position provides some advantage in terms of deflecting and deferring eventual cooling loads, while there is only limited evidence of impact in terms of positioning for postponing heating loads. Further studies in larger scale experiments will be pursued to verify these initial findings.

CONCLUSION

Experiments have been performed on three types of specimens incorporating a PCM in the different positions of a wall cavity. Both numerical and graphical result of PCM responses across all experiments have been studied. The effects of PCM positioning on thermal comfort and load shifting were measured for alternated but periodically fixed cold and warm exterior climate cycles. The results of these assessments indicate that wall elements with PCM in exterior cavity positions show a more practical position towards thermal comfort. Either position showed significant lag times, specifically when moving from cold to warm exterior climate periods. There again, walls with PCM in the exterior position achieved a slightly bigger lag time than walls with PCMs on the interior side.

This study did not take into account broader impacts on overall energy consumption, or measurements of median radiant temperatures for an entire space, which could add further evidence to the comparison. Overall, the study demonstrates some advantages for PCMs to be installed towards exterior positions of a wall cavity, but further studies will be conducted to verify this observation with larger-scale experiments and in connection with other material combinations.

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Performance Evaluation of Wall Panels Incorporating New and Innovative Materials Developed with High Insulation Properties

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ABSTRACT

Thermal insulation is a key factor in building design to improve energy performance and thermal comfort. There are many types of widely used insulation materials in the current market; however, even though the R-values are generally available, limited quantitative research results on the performance of such materials are available. The study presented in this paper is focused on evaluating the energy efficiency and cost competitiveness of residential wall panels incorporating both conventional and/or innovative insulation techniques. Combinations of different conventional and innovative insulation materials are also analyzed for different regions. A hygrothermal analysis was also performed to assess the condensation potential of these types of insulation materials.

INTRODUCTION

The energy consumption of the U.S. residential buildings accounts for 22% of the total energy use, with about 42% due to heating and cooling loads. One effective way to decrease the space heating and cooling energy is to improve the building envelope performance, which accounts for 36% of the overall building energy consumption due to heat gain and loss (Cooperman and Dieckmann, 2011). This study mainly evaluated the performance of several types of conventional and innovative insulation materials that can be used in wall panels. The study uses simulation to compare energy saving potentials of several insulation materials, such as EPS, XPS, polyisocuanurate, aerogel and vacuum insulation panel.

LITERATURE REVIEW

Conventional Insulation Materials

There are several types of commonly used insulation materials for walls, including cellulose fibers, fiberglass, expanded polystyrene (EPS), extruded polystyrene

(XPS) and rock wool. This section briefly introduces some of these conventional insulation materials and their properties.

Cellulose Fiber. Cellulose fiber insulation (CFI) products are made of paper stocks mixed with other chemical components to increase resistance to fire and corrosion and to impart other desired characteristics. The thermal resistance (R-values) usually varies within an acceptable range from 3.5-3.9 (R/in.), and the density is about 24-56 kg/m^3 for sprayed type (cavity) (CIMAC, 2009). It also performs well with acoustic control, with a noise reduction coefficient of approximately 0.75. Some studies (Ojanen and Laaksonen, 2016) have shown that one of the important characteristics of cellulose fiber is its hygroscopicity property, which means that rather than being considered as a complete vapor barrier, it will let moisture pass through in a buffering way. Accordingly, this effect can regulate (smooth down) the humidity variation so the structure can maintain a stable relative humidity level and therefore maintain comfortable indoor conditions.

Mineral Wool Insulation. Mineral wool is made of melted raw materials such as stone, dirt, slag and other chemicals, which are then turned into thin fibers that are then adhered together after being coated with binders and slightly compacted to form insulation batt or boardstock (Buildinrgreen, Inc.). Mineral wool has high fire resistance without any use of other 'flame retarders', and is a heavier and denser material compared with fiberglass batt insulation, which then attains a good sound control property. Moreover, since the components of mineral wool are mostly recycled materials. The acceptable range of R-value for mineral wool is generally considered as 3.1-3.4 (per inch) (Great Day Improvements, LLC). Besides, compared with fiberglass and rigid foam board insulation, mineral wool is harder to operate and may require special care (Buildinrgreen, Inc.).

Rigid Board Insulation. The following three commonly used rigid board insulation types are chosen for discussion here: expanded polystyrene (EPS), extrude polystyrene (XPS) and polyisocyanurate, which is usually referred as polyiso. A brief introduction of each of these rigid board insulation follows.

<u>Expanded Polystyrene (EPS):</u> Used in walls, roofs and floors, EPS with R-value in the range of around 3.6-4.0 per inch has the lowest R-value among these three insulation materials, but is the most affordable of the three, meaning that it has the highest R-value per dollar (InsulFoam Company). However, it can be more easily damaged than the other two. It is available in faced or unfaced forms, with the faced EPS form also functioning as a vapor retarder (InsulFoam Company). While both EPS and XPS look similar, EPS is actually lighter (less dense).

<u>Extruded Polystyrene (XPS):</u> XPS in the form of blue or pink board has both the cost and R-value in the middle range of these three types of rigid-foam insulations (InsulFoam Company). Because it is stronger and denser than EPS, XPS boards

are typically used in walls and below-grade slabs and foundation walls. XPS is considered semipermeable and therefore, with faced form it may also be considered as a vapor retarder, but not vapor barrier. The generally accepted R-value for XPS is around 4.5-5.0 per inch thickness (InsulFoam Company).
Polyisocyanurate: Polyisocyanurate often referred as polyiso is the most expensive one of these three rigid-board insulations. It also has the highest R-value, often considered as high as 7.0-8.0 per inch. There is a reflective foil facing on both faces of the board, giving it significant resistance to radiant heat transfer. A reported issue with polyisocyanurate is that with the gas trapped in the cells escaping, the R-value may slightly decrease over time (InsulFoam Company). According to prices offered by InsulFoam Company, the normalized prices for these three types of rigid-foam insulation are shown in Table 1.

Table 1 R-values of rigid-board insulation (InsulFoam Company)

Rigid foam insulation	R value per inch thickness	Cost ($) per ft^2 per inch thickness	R-value per inch thickness per dollar per ft^2
EPS	3.6-4.0	0.19	18.95-21.05
XPS	4.5-5.0	0.42	10.71-11.9
Polyisocyanurate	7.0-8.0	0.7	10-11.42

New insulation Technologies

Vacuum Insulation Panels. One of the most effective solutions is to insulate the building envelope using vacuum insulation panels (VIP), which offers very effective insulation within limited thickness and can have a thermal conductivity typically ranging from 0.004W/(mK) to 0.008W/(mK) even after 25 years of service (Kalnæs and Jelle, 2014). A VIP usually consists of a porous core enveloped by multiple layers. The use of porous material with small pore sizes enables the inside air to evacuate while also supporting the outside envelope layers. Since the core provides both thermal and mechanical properties to the insulation, there are some requirements when people choose the core materials. The core diameter needs to be small and the core structure needs to be fully open to allow air to evacuate. Because the core also undergoes compression, it needs to have sufficient strength. Another important point is to have the core material impermeable to infrared radiation to reduce the radiative heat transfer and thus provide the expected thermal performance. Different core materials have been used today, such as fumed silica, polyurethane foam and glass fibers have already been used for this purpose (Kalnæs and Jelle, 2014).

One of the most important issues associated with VIP is that their thermal resistance deceases over time because it highly depends on the low inner gas pressure. With air penetration or outgassing effect from inside over the life time of the VIP, the gradual loss of vacuum (or very pressure) decreases the performance and lowers its effectiveness. Therefore, getters and desiccants are placed inside the panel to absorb the air and vapor penetrating into the VIP. That helps the panel maintain a required low level of inner gas pressure while opacifiers may also be used to reduce the radiative heat loss (Kalnæs and Jelle, 2014).

Gas-filled Panels. Gas-filled panels consist of three parts: gas barrier, gas baffle and the gas sealed inside. All components of GFPs serve a distinct function and are critical to its thermal performance. GFP offers a potential for the envelope to yield buildings that may not require heating energy while reducing the building costs and not needing major changes in typical frames (Griffith et al., 1995).
The gas sealed in the panel is the most important component to make GFPs a high-performance thermal insulation. High-performance GFPs can be achieved by using gases with low thermal conductivity, which is lower than air or air itself, and thus reduce the heat transfer through it. Typically, inert noble gases such as argon and krypton are used. Air-filled panels have a thermal conductivity of about 0.029W/(mK). One advantage of GFPs filled with argon is the abundance of argon gas at low cost and a conductivity of about 0.02W/(mK), which is almost as low as typical foam board insulation can reach. However, Krypton can achieve an even lower conductivity as 0.012W/(mK) (Griffith et al,1995). The barrier is a hermetically sealed enclosure to retain the gas filled inside. It should act in both directions: to prevent the outside air penetrating inside the panel and to prevent the sealed air leaking out (Baetens et al., 2010). It is usually bonded to the surface of the baffle and supported by the baffle and the gas to maintain a flat shape. Most GFP barriers are made of food packaging films (Griffith et al., 1995).

The baffle typically has a cellular honeycomb structure and is assembled in a flat stack form and expanded to create the inside cavities (Griffith et al., 1995). Because of the long conduction path compared with its thickness, solid thermal conduction can be minimized. The baffle is necessary to decrease the heat convection and radiation inside the panel. The radiation heat transfer is decreased by using low-emissivity cavity surfaces, such as the inexpensive metallized thin polymer films. However, the number of layers and cavities need to be carefully designed to reach both desirable thermal performance and also cost effectiveness (Baetens et al., 2010).

Phase Change Materials. Phase change material (PCM) is one of the new smart materials that can be used in building envelope systems. Unlike most insulation materials whose capacities depend on the mass of the body of material itself and the specific heat capacity to withstand the external heat without warming up the inside rapidly, PCM acts in the way that it can absorb the external heat in the form of latent heat, which means it undergoes a phase transition, for example from solid to liquid (Casini, 2014). During daytime, when the temperature exceeds a critical level (often referred as "melting point", typically between 23°C and 26°C), it activates the PCM and starts the phase change. The exterior heat is then subtracted from the environment and used for PCM to experience phase transition (i.e., Solid to liquid). Then during night time when temperature drops below the set point, the reverse phase transition (liquid-solid) occurs and thus releases heat to the environment, which can be used to warm up the building during the night. Considering PCM increases the building thermal mass, the cooling load in the summer will be decreased, and thus a thinner insulation system is possible (Casini 2014). Different PCM materials have been used and their properties as published by Casini (2014) are listed in Table 2.

Table 2. PCM materials and properties (Casini, 2014, reproduced by authors)

Material	Fusion temperature (°C)	Latent Heat (kJ/kg)
Paraffin	6-76	170-269
Non-paraffin	8-127	86-259
Fatty acids	17-102	146-242
Salt hydrates	14-117	68-296
Eutectics	15-82	95-218
Water	0	333

Aerogel. Aerogel is the solid component of a silicon gel isolated from its liquid component, i.e., what will be left over if the liquid part of a gel is removed while the volume not significantly changed (Filate, 2014). It has nano-porous structure and the thermal conductivity can be as low as 0.015W/(mK), which makes it possible for good thermal insulation of building envelope system. Currently, there are very few types of commercial aerogel products in the U.S. Aerogel can be blended with other materials to make an opaque insulation board, which is it's neither flammable nor hydrophilic. A German BASF Chemical Company invented a high-performance aerogel thermal insulation called SLENTITE Aerogel insulation board (Filate, 2014). Due to its very low density (0.0011 to 0.5 g cm^{-3}), this material is relatively easy to handle and install boards of any thickness. Filate (2014) shows a comparison of the wall insulation thicknesses needed to achieve a wall U-value of 0.26 $W/(m^2K)$. Compared with the 115mm thickness needed for Mineral Wool insulation, and the 87mm thickness needed for Polyurethane insulation board, SLENTITE shows a better performance as a required thickness of 50mm (Filate, 2014). A recent study done by Jingduo Feng et al. (2016) shows that the hybrid of silicon aerogel and cellulose fibers has been successfully developed and the thermal conductivity of the hybrid is about 0.04W/mK.

COMPUTER MODEL

General Information

This section compares different insulation technologies discussed in the previous section based on their energy performance. For this purpose, a 'reference house' preferably without any type of wall insulation is needed to explore and compare the effectiveness of the conventional and innovative thermal insulation technologies chosen for the study. According to Building America House Simulation Protocols (U.S. Department of Energy), BEopt offers a B10 benchmark house with typical properties for reference purpose (Hendron and Engebrecht, 2010). For this purpose, data obtained from U.S. Department of Commerce website for single-family houses is used to build our model in BEopt. The most common case of floor area, number of stories, bedrooms, bathrooms and foundation should be selected. Table 3 summarizes the data selected for modeling, which is chosen from Year 2010 to represent the recent single-family houses.

Table 3. Summary of geometric inputs

Geometric Properties	Values
Square feet of floor area	Round to 2610 (1305*2stories)
Number of bathrooms	2.5
Number of bedrooms	3
Number of stories	2
Type of foundation	Full or partial basement

Conventional Insulation Modeling

In this section, several conventional insulation materials are modeled and compared with the benchmark house with no insulation behind OSB sheathing and assumed to be located in Pittsburgh, PA. In order to modify the wall sheathing properties in BEopt to include thermal resistance, the insulation properties and associated costs listed in Table 4 are used. BEopt does not have these insulation materials pre-defined, so a user-defined case will be generated for each insulation type. Each insulation type is assumed to be part of the wall OSB sheathing for simulation runs as compared with the reference house case.

Table 4. Conventional material properties

Insulation Material	R-Value (per inch)	Cost ($/ft^2/thickness)
Cellulose Fiber	3.7	0.4
Mineral Wool	3.3	0.6
EPS	3.8	0.19
XPS	4.8	0.42
Polyisocyanurate	7.5	0.7

**The R-value and price based on commonly acceptable range in the market offered by companies.*

Innovative Insulation Modeling

In this study, the following three types of innovative insulation materials are modeled in BEopt: vacuum filled panels, phase change materials and aerogel. To model the vacuum filled panels and aerogel, the R-value and unit costs are modified in BEopt to define a new type of wall sheathing. To model phase change material, a thermal mass property different from that assumed for the benchmark building is used. The modifications made are listed in Table 5.

Table 5. Innovative material properties

Insulation material	R-Value (per inch)	Cost ($/ft^2)
Vacuum filled panel	25*	10 *(per inch)
Aerogel	15*	2.5*per 10mm (6.35/inch)

** The references of R-value and cost in Table 5 are listed in http://e3tnw.org/ItemDetail.aspx?id=531 and Shukla et al. (2012).*

BEopt Results and Analysis

BEopt runs the analysis and shows the source energy consumption and the energy-related cost for each case. Source energy represents the total amount of raw fuel that is required for building operations such as heating, cooling and lighting, which will be affected by the choice and type of insulation as shown in Figure 1, which illustrates the effect of the type of insulation material on the amount of source energy use for different building operation. The result from BEopt analysis is shown in Figure 1.

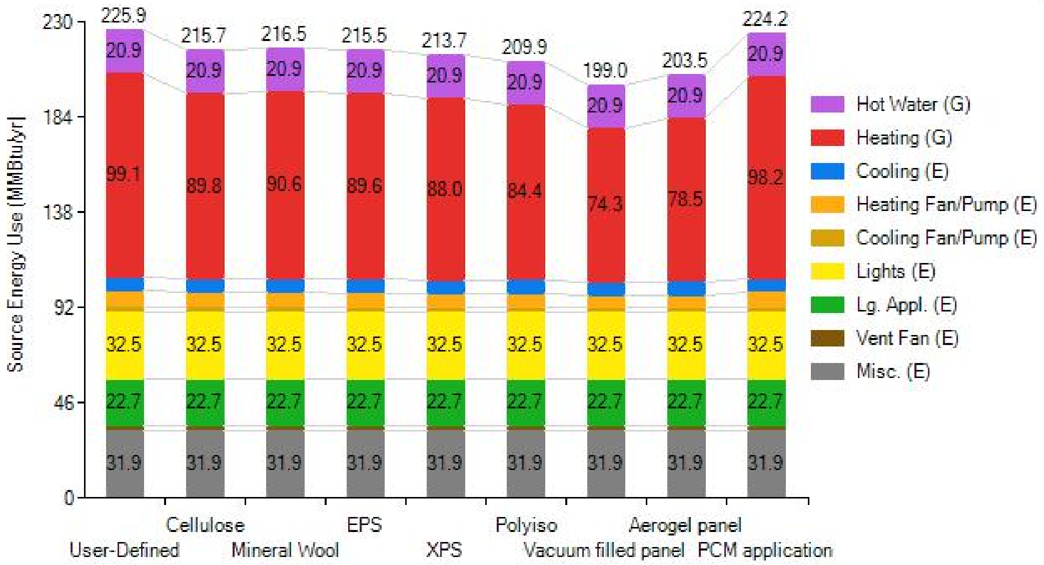

Figure 1. Source Energy Use of different insulation materials

As expected, the results show that with different types of insulation materials, the source energy consumption due to heating is different. All other sources of energy consumption, such as lights, hot water and ventilation, are the same because the difference in insulation materials does not affect such energy consumption. For example, the source energy consumption by the Benchmark building is 225.9 MMBtu/yr with the part due to heating being 99.1 MMBtu/yr or 43.9%.

Table 6. Total initial cost increase (only show the difference)

Insulation type	Initial cost ($)
Benchmark	0
Cellulose Fiber	934
Mineral Wool	1407
EPS	436
XPS	981
Polyisocyanurate	1644
Vacuum filled Panel	23653
Aerogel	15010
PCM	21069

The initial cost is the energy-related cost of the building. The difference in initial costs represents the upfront material and labor costs for each type of insulation material. Since the only difference we set in our model is the types of insulation materials, the initial cost difference comes only from the material price difference. Considering the Benchmark building as the reference, all other values greater than zero show how expensive the insulation is compared with the case of no insulation use. For example, as shown in Table 6, the initial cost of the case with 1in. thick EPS insulation is $436 more than the benchmark house, while the one with 1in. thick aerogel insulation costs $15,010 more than the benchmark house. Figure 1 shows that all types of conventional insulation materials work effectively to reduce the annual source energy consumption mainly by lowering the heating energy demands. Among those, the Polyisocyanurate rigid board insulation shows the best performance -- a source energy saving (compared to the reference house) up to 7.1% per year. However, the polyiso is also the most expensive one. Aside from polyiso, the next best performing insulation is XPS, with the initial cost almost the same as Cellulose Fiber, XPS has a source energy saving up to 5.4% per year. However, it is worth mentioning that EPS performs relatively as good as other thermal insulation, while it is more affordable than all other materials with an increment of initial cost as only $436. This cost just comes from the price difference of insulation materials with a rough wall area of 2368 ft^2. Therefore, if we consider the initial cost, EPS seems to be the most affordable.

As for the innovative technologies explored, the vacuum filled panel shows the best performance among all types of insulation, up to 11.9% of annual source energy saving. The results show that aerogel is the next best performing insulation material with a source energy saving of 9.9% (compared to the reference house). It should also be noted that although vacuum filled panel shows the best thermal performance, it is also the most expensive type of insulation with an initial cost increment of $23,653 (due to the price difference for insulation materials with a wall area of 2368 ft^2) compared to the reference house. On the other hand, with $15,010, the initial cost of aerogel panel is much less than that of vacuum filled panels.

Table 7. Source Energy Saving (Normalized)

Insulation type	Source Energy Saving(%/yr)	Source energy saving（%） per dollar
Benchmark	0	0
Cellulose Fiber	4.5	0.0048
Mineral Wool	4.2	0.0030
EPS	4.6	0.0106
XPS	5.4	0.0055
Polyisocyanurate	7.1	0.0043
Vacuum filled Panel	11.9	0.0005
Aerogel	9.9	0.0007
PCM	0.7	0.00003

Normalization of the energy saving per unit cost per unit area will provide a more meaningful comparison of the cost effectiveness of the products. Such normalization is shown in Table 7, where % energy saving per dollar is listed. As an example of how these values were calculated, let's consider EPS. The house with EPS has a source energy saving of 4.6%/yr, and the initial cost increment compared with the benchmark house is $436. This gives a normalized source energy saving 0.0106% [4.6%/$436 (cost increment)]. Considering the normalized source energy saving per dollar, as shown in Table 7, EPS shows the best cost-effective performance with the highest R-value available at the lowest price. XPS is the second best performing insulation. It can be observed that the normalized source energy saving of aerogel and VIPs are, respectively, 7% (0.0007/0.0106) and 4.7% (0.0005/0.0106) of the normalized source energy saving of EPS, even though they have very high R values. This is due to the fact that the prices of these materials are too expensive to be considered as cost-effective insulation materials. The PCM as incorporated in drywall shows a small amount of source energy saving, e.g., 0.7%, but it has a much higher initial cost compared with other types of insulation. That indicates that PCM is not suitable to be used independently and without the use of other types of insulation.

For realistic cases, we often aim at a wall assembly of certain R-value. To achieve a certain R-value, by using different types of insulation, the thickness of the wall insulation will be different, meaning that insulation types with higher R-value will lead to a thinner wall and thus give the builders more internal space. Assume that an R-12 wall is desired; then the results obtained from previous analyses are summarized in Table 8. As shown in Table 8, to achieve an R-12 wall, using only EPS leads to an insulation layer of 3.16-inch thick, while using aerogel only has a thickness 0.8 inch. However, using aerogel costs 3342.7% more than EPS.

Table 8. Properties and cost for different types of insulation materials

Insulation type	R-value per inch	Thickness for a R-12 wall	Cost for 2368 ft^2 wall area (compared to the benchmark)	Percentage cost increase compared with EPS (%)
EPS	3.8	3.16	436	0
XPS	4.8	2.50	981	125
Polyiso	7.5	1.60	1644	277
Cellulose fiber	3.7	3.24	934	114
Mineral wool	3.3	3.64	1407	222
VIP	25	0.48	23653	5325
Aerogel	15	0.80	15010	3342

Combination of Different Insulation Types

In this section, different combinations of insulation types are analyzed at different locations to compare the performances with the benchmark house. For this BEopt analysis, we assume a 3-in. thick total insulation layer made up of different combinations. For example, the combination of EPS board with aerogel consists of a 2-inch thickness of EPS and 1-inch thickness of aerogel, thus many different combinations can be considered. BEopt results are listed in Table 9 for three different locations: Pittsburgh, Atlanta and Los Angles. The source energy saving and the initial cost increments are compared.

The results indicate that when the thickness of insulation layer is fixed, a combination of conventional materials with vacuum filled panel or aerogel shows an apparent improved performance compared with the case of only conventional materials. Varying the location shows that as expected the effect of all types of insulations is more pronounced in cold regions compared with warm regions. For example, EPS working alone can lead to a source energy saving of 8.8% in Pittsburgh, while only 3.7% in LA. Combinations with VIPs, as discussed earlier, are much more expensive than with other types of insulation. However, the results show that those with aerogel panels are more affordable and also highly effective. Even though the price might be unfavorable, yet PCM works effectively with other types of insulation resulting in relatively high source energy saving as listed in Table 9.

Table 9. Source energy saving of different combinations at different locations

Locations / Combinations	Pittsburgh	Atlanta	Los Angles
EPS (2'') + VIP (1'')	12.8%	9.1%	4.7%
EPS (2'') + Aerogel (1'')	11.5%	8.2%	4.4%
EPS (3'')	8.8%	6.4%	3.7%
Cellulose Fiber (2'') + VIP (1'')	12.8%	9.1%	4.7%
Cellulose Fiber (2'') + Aerogel (1'')	11.5%	8.2%	4.4%
Cellulose Fiber (3'')	8.7%	6.3%	3.7%
EPS (3'') + PCM	9.3%	7.2%	4.9%

Table 10. Initial cost ($) increment of different combinations at different locations

Locations / Combinations	Pittsburgh	Atlanta	Los Angles
EPS (2'') + VIP (1'')	24550	24570	24570
EPS (2'') + Aerogel (1'')	15910	15920	15940
EPS (3'')	1320	1340	1350
Cellulose Fiber (2'') + VIP (1'')	25550	25560	25560
Cellulose Fiber (2'') + Aerogel (1'')	16900	16920	16930
Cellulose Fiber (3'')	2830	2830	2840
EPS (3'') + PCM	22390	22400	22420

Table 11. Normalized source energy saving (%) per dollar

Locations / Combinations	Pittsburgh	Atlanta	Los Angles
EPS (2'') + VIP (1'')	0.0005	0.0004	0.0002
EPS (2'') + Aerogel (1'')	0.0007	0.0005	0.0003
EPS (3'')	0.0067	0.0048	0.0027
Cellulose Fiber (2'') + VIP (1'')	0.0005	0.0004	0.0002
Cellulose Fiber (2'') + Aerogel (1'')	0.0007	0.0005	0.0003
Cellulose Fiber (3'')	0.0031	0.0022	0.0013
EPS (3'') + PCM	0.0004	0.0003	0.0002

Table 11 shows the normalized source energy saving, meaning the saving that can be achieved per dollar. Take the case of 3-inch thick EPS insulation as an example. The source energy saving of using 3-inch EPS in Pittsburgh is 8.8%, and the corresponding initial cost increment compared to the benchmark house is $1323. So the normalized source energy saving is 8.8%/$1323, which is 0.0067%/$. It can be observed that even though innovative materials like aerogel have desirable thermal performance, due to their high prices, the use of such materials is not cost-competitive. Traditional insulation materials such as EPS perform about ten times better than innovative materials at the same cost. For example, using the combination of EPS (2'' thick) and aerogel (1'' thick) costs more than ten times ($15910) the use of only EPS ($1323), and the normalized source energy saving of EPS with aerogel is also more than ten times larger than the normalized source energy saving of only EPS, even though the R value of aerogel is much higher than EPS.

WUFI ANALYSIS

In this study, WUFI analysis is also performed to show the condensation potential of those insulation materials discussed above. WUFI ORNL 5.3 (https://wufi.de/en/) is used and due to the software limitation, the innovative materials such as aerogel cannot be analyzed in the non-commercial WUFI version. Thus, the condensation evaluation mainly focuses on the EPS, XPS and cellulose fiber. The wall system constructed in WUFI consists of an exterior vinyl finish, a lime silica brick layer, a drainage cavity, the insulation material layer, an interior lime silica brick layer and the interior plaster layer, which is a similar case as Ramaji's model (2015). The wall section is shown in Figure 2. For WUFI input, walls with up to 10 ft high are considered part of short buildings. The orientation is assumed in the north direction and the inclination upright (90°). The rain water absorption is assumed 70% and limestone bright is selected to define the radiation absorptivity. The initial relative humidity is defined as 80% and the initial temperature assumed 20°C. The calculation period is set for 2 years and the time step assumed one hour. The climate region is selected to be Pittsburgh, PA with the climate data shown in Figure 3, which shows the variation of the temperature and relative humidity throughout the year, as well as the solar radiation and driving rain conditions.

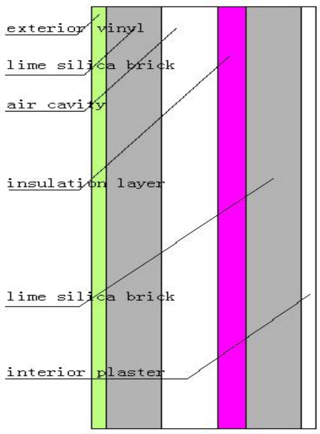

Figure 2. Wall section analyzed

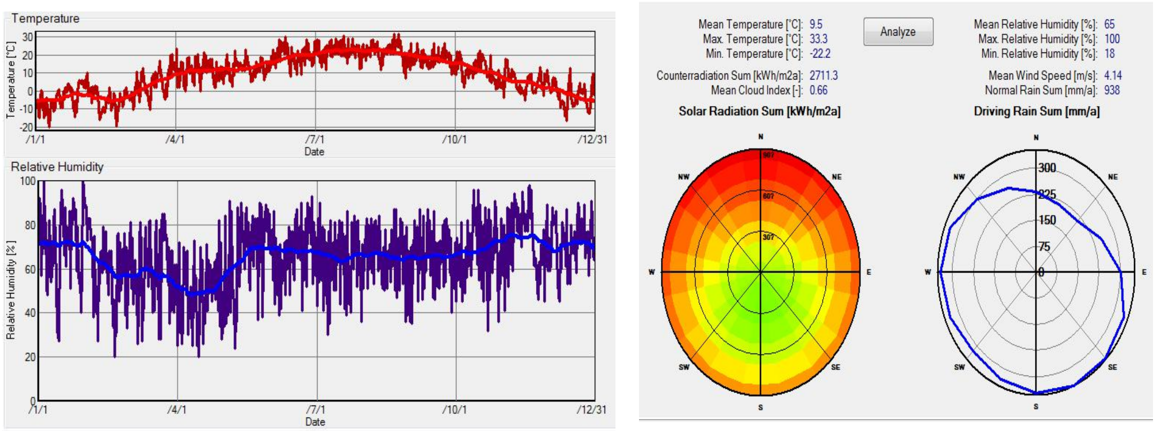

Figure 3. Climate data of Pittsburgh in WUFI

The results of WUFI analysis show that for all these three types of insulation, the total water content in the wall system decreases over time and the water content in insulation layers varies with respect to different seasons. For example, Figure 4 illustrates the change of total water content (kg/m^2) in EPS case. If the total water content is increasing, then that means we have moisture accumulation problem. Figure 5 describes the change of water content (kg/m^3) in EPS layer. Note that if we have water contents of different layers as (*n1, n2, n3*) and the thickness for each layer as (*t1, t2, t3*), then the total water content can be calculated as: *T=n1*t1+n2*t2+n3*t3.* The analysis shows that the water content variation for the cellulose fiber insulation layer is also the largest. This indicates that for cellulose fiber insulation, sealing joints becomes an important consideration as water penetration issues will be more sensitive compared to other options. As for condensation potential, for all three cases, the WUFI analysis results show that the temperature of exterior and interior surfaces always remains higher than the dew point temperature throughout the year, meaning that the systems have low vulnerability to both exterior and interior condensation. Accordingly, one may conclude that with these three types of insulation, the condensation will not be a problem.

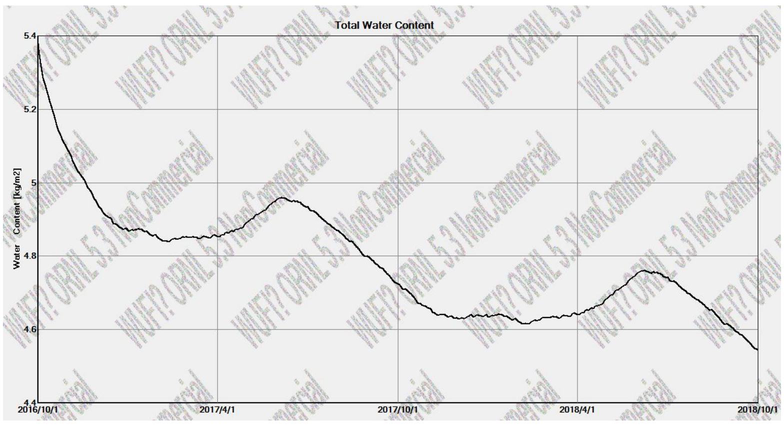

Figure 4. Total water content of wall (per area) with EPS insulation

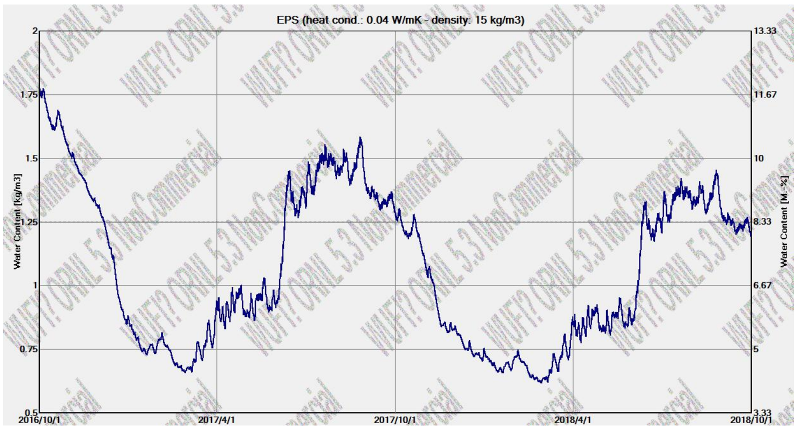

Figure 5. EPS layer water content (per volume)

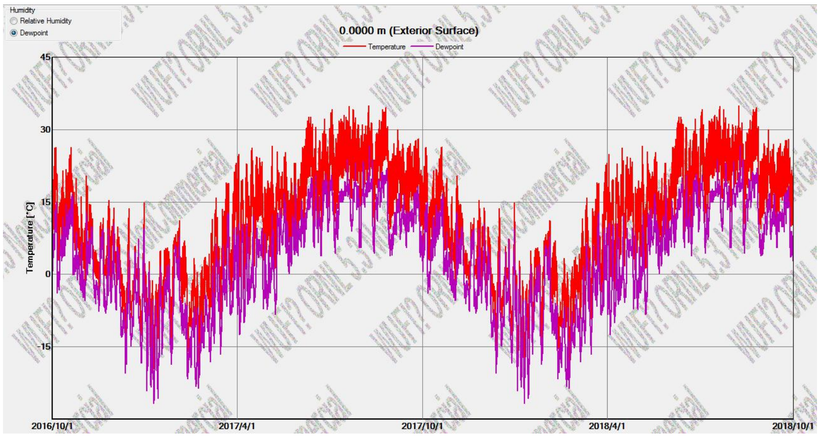

Figure 6. Exterior surface temperature vs. dew point（EPS）

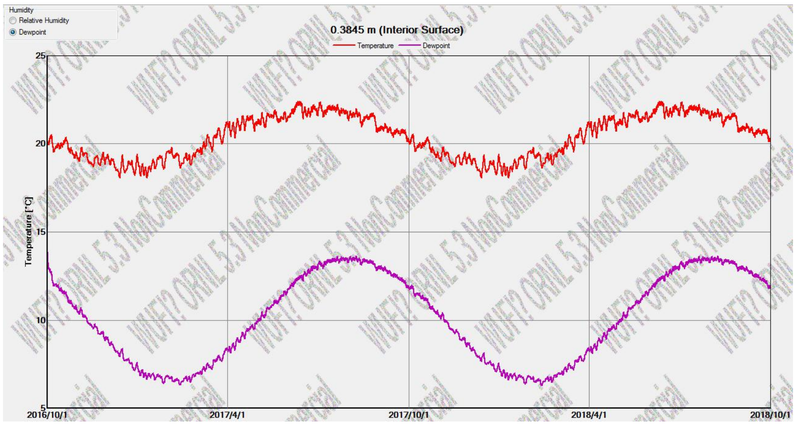

Figure 7. Interior surface temperature vs. dew point (EPS)

DISCUSSIONS AND CONCLUSIONS

In this study, some of the emerging as well as traditional residential building insulation technologies were considered for a side-by-side comparison. The results show that in conventional insulation materials, the polyisocyanurate panel has the best performance with up to 7.1% source energy saving, but EPS panel is also a good choice with 4.6% source energy saving and is more affordable compared with polyiso. As for the innovative materials, the Vacuum filled Panels performs much better than all other materials (up to 11.9% source energy saving) but it is also the most expensive one with an initial cost increment of $23,650 compared with the Benchmark house (the initial cost of Benchmark house is listed as zero to show the ‘initial cost difference’ of each cases). However, aerogel panel also has a considerable energy saving (9.9%) with much lower price compared with VIP (an initial cost increment of $15,010 compared with the Benchmark house). In general, the innovative insulation technologies perform better (around 10% source energy saving) than the conventional ones (mostly around 5% source energy saving), which is expected. However, when considering the normalized source energy saving per dollar (the amount or percentage of energy saving we can get for one dollar at unit area), the innovative materials are not competitive. Aerogel and VIPs, although working highly efficiently as insulation materials, perform respectively 14 and 20 times less desirable compared with EPS when considering their cost, meaning that they are not cost-effective at this time. The analysis also shows the advantages and disadvantages associated with different types of insulation. To obtain an R-12 wall, only 0.8-inch thick aerogel insulation layer is needed compared to EPS of 3.16 inches, which means by using innovative materials we can design thinner walls and thus larger floor areas. However, using aerogel also leads to a cost of 30 times higher than EPS. Nonetheless, considering the benefits of additional floor areas, such extra insulation costs may be easily absorbed for certain projects. The WUFI analysis shows that for the three cases considered, condensation will not be a problem.

When taking different combinations of insulation into consideration, it is observed that the combination of conventional materials with aerogel panel shows good performance (more than 10% source energy saving in cold regions) with a relatively more affordable price compared to just aerogel. However, the normalized source energy shows that traditional materials are still the most cost-competitive. Even though innovative materials perform well, and a higher R-value per thickness can be reached, at this time, they will not be affordable for most builders.

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A Brief Literature Study of Nanoparticles Supplementation in Civil Cementitious Materials

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Abstract

Multifunctional concrete has such applications as dwellings thermoelectric energy management, collection of solar energy, condition/damage evaluation through self-sensing, and self-healing. Nano-scale modifications through use of nanomaterials together with atomic architecture re-arrangement are necessary if reduction in dose of the conductive macro fillers are desirable in order to fine-tune the multifunctional concrete. This is one rationale behind increasing studies of nanomaterials in the past decade. In this paper, a short literature survey of several nanomaterials utilized in civil cementitious materials is presented. Nanomaterials' higher surface area may not translate to desirable macroscopic properties given their high tendency of aggregation and their intrinsic small dimensions. Further studies are needed to identify the areas these materials excel at and alterations needed plus the areas where their synthesization cost does not justify their inclusion. An extensive experimental program is being undertaken with the ultimate goal of evaluation of concrete durability, multifunctionality and mechanical properties. Additionally, in order to have a better understanding of the Mars habitats possible alternatives, geopolymers using Martian/lunar regolith simulants under simulant environmental conditions are studied.

Introduction

Effects of incorporation of particles with finer or comparable sizes to cement particles in the cement paste, mortar, and concrete specimens have been studied extensively in literature. More conventional supplementary cementing materials (SCMs) such as fly ash, blast-furnace slag, and silica fume are widely utilized for such benefits as delay in generation of the hydration heat, mitigation of alkali-aggregate reactions, more compact and durable micro-structures, etc. Additionally, some of these pozzolanic wastes (e.g., fly ash and slag) can be activated by using high-alkaline solution to replace 100% of portland cement paste in making concrete; these alternatives to portland cement concrete, alkali-activated concrete, have been vastly studied [1–5]. SCMs possess various degrees of pozzolanic and hydraulic activities and undergo chemical reactions and physical bonds with cement hydration products and water. While addition of fly ash, as a result of its spherical shape, provides a more workable mixture, silica fume due to its finer sizes leads to a thicker mixture when compared to control ordinary portland cement (OPC) mixtures with no addition of SCMs. Silica fume particles exhibit larger attractive forces and tend to agglomerate more easily. The larger surface area of silica fume particles provides more deposit sites for the hydration products such as portlandite and expedite the pozzolanic activities. This favorable outcome very much depends on how easily the hydration products have access to the silica fume particles. This is dictated by deagglomeration of silica fume particles using surface functionalization or physical repulsion provided by water-reducing admixtures.

In the past decade, studies on the advantages of nanomaterials inclusion in concrete have escalated in parallel to other research fields [6]. Reduction in the production costs, advances in material characterization techniques together with the inherent filler, reinforcement effects, and large surface areas of the nanomaterials and the progress towards their more environment-friendly productions make them economically and sustainably potential additions to the concrete civil infrastructures. These materials excel at fine-tuning properties of concrete in energy harvesting and self-sensing applications where materials' nano-scale re-arrangement to obtain a composite multifunctional system is essential.

The most-extensively-studied nanomaterials with applications in concrete are:

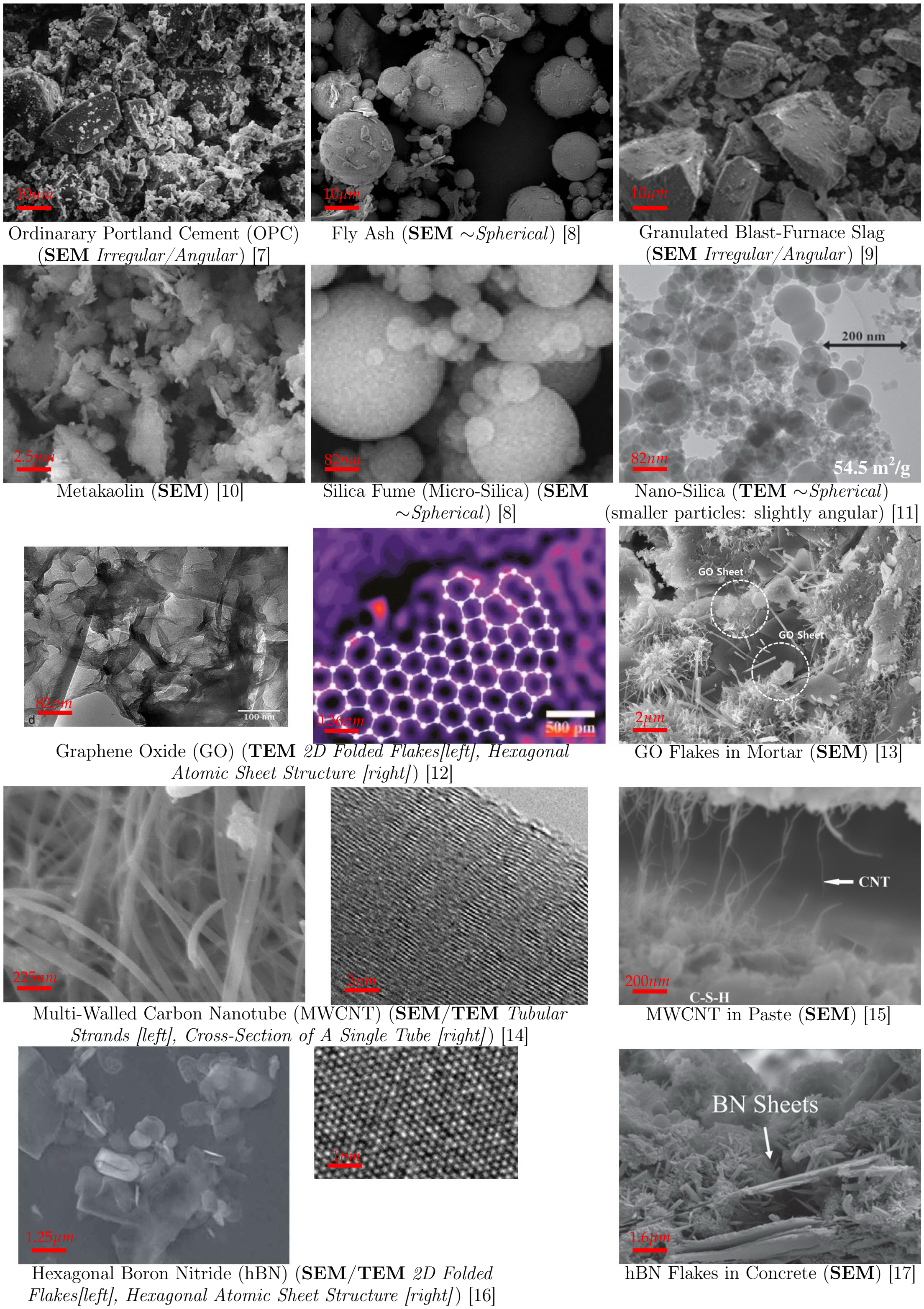
- Nano-silica (NS) and nano-titania.
- Carbon nano-fibers (CNF).
- Carbon nano-tubes (CNT) in the form of single-walled carbon nano-tubes (CWCNT) or multi-walled carbon nano-tubes (MWNTs).
- Graphene nano-platelets (GNP) and graphene oxides (GO).
- Boron nitride (BN).

Their agglomeration and affinity with cementitious hydrates vary depending on the synthesization methods, particle size distributions and geometries among other factors. Figure 1 illustrates a comparison among few electron microscopy images of micro/nano-meter-sized particles collected from literature [7–17].

Development of outher space habitats and human and dwellings shielding are where nanomaterials have been explored in literature (e.g, see [18]). Cementitious materials in additive manufacturing of Mars habitats has been the subject of recent NASA competitions. Nanomaterials supplementation can be studied in order to improve properties of such materials.

Nanomaterials evince significantly larger agglomeration in the cement pore solution necessitating appropriate dispersion methods and functionalization techniques for their usefulness. While various dispersion methods such as shear mixing, ball milling and stirring have been used in literature [19], ultrasonication has usually been reported among the most efficient methods. Excessive energy of dispersion input in the solution has been revealed deleterious in the dispersion due to significant breakage of some nano particles such as carbon nano-tube. Sole usage of ultrasonication often does not yield a widespread distribution of the nano particles in the pore solution. On the other hand, incompatibility of these nanomaterials in their pristine condition (not chemically nor physically modified) with the cement hydrates is observed resulting in mitigation of chemical bonds between them hence the possibility of their inclusion worthlessness.

As in the case of silica fume supplementation, physical surface functionalization using surfactants such as superplasticizers (high-range water-reducing [HRWR] admixtures) may be essential depending on the nanomaterials. The molecular structure of the surfactant is one of the most consequential factors in efficacy of the dispersion. The three main categories of superplasticizer surfactants used in concrete are polymelamine sulfonate (PMS), polynaphthalene sulfonate (PNS), and polycarboxylate (PC) -based admixtures. PMS and PNS -based surfactants counteract the absorption tendency of the cement hydrates in OPC mixtures by electrostatic repulsion while more modern PC-based surfactants predominantly take part in steric repulsion taking advantage of their long backbones. The comb-shaped PC-based surfactants are often reported to have a more substantial influence in retaining workability [20]. Plank et al. [21,22] evaluated impact of eight ester-based polycarboxylates (PCEs) with MPEG chain architecture on dispersion of MWCNT in deionized water. They suggested the MPEG-PCE admixture with longer molecular backbone and higher side chain densities / grafting densities excelled at disassembly of MWCNT in the aqueous dispersion. Same researchers evaluated the effect of methacrylate-based and allylether-based PCEs on dispersion of silica fume (at 16% replacement of cement by weight) in cement pore solution and concluded the former is predominantly useful in dispersion of cement while the latter is more beneficial in dispersion of silica fume [23]. Therefore, a combination of both admixtures was reported more effective.



Ordinarary Portland Cement (OPC) (**SEM** *Irregular/Angular*) [7]

Fly Ash (**SEM** $\sim$*Spherical*) [8]

Granulated Blast-Furnace Slag (**SEM** *Irregular/Angular*) [9]

Metakaolin (**SEM**) [10]

Silica Fume (Micro-Silica) (**SEM** $\sim$*Spherical*) [8]

Nano-Silica (**TEM** $\sim$*Spherical*) (smaller particles: slightly angular) [11]

Graphene Oxide (GO) (**TEM** *2D Folded Flakes[left], Hexagonal Atomic Sheet Structure [right]*) [12]

GO Flakes in Mortar (**SEM**) [13]

Multi-Walled Carbon Nanotube (MWCNT) (**SEM/TEM** *Tubular Strands [left], Cross-Section of A Single Tube [right]*) [14]

MWCNT in Paste (**SEM**) [15]

Hexagonal Boron Nitride (hBN) (**SEM/TEM** *2D Folded Flakes[left], Hexagonal Atomic Sheet Structure [right]*) [16]

hBN Flakes in Concrete (**SEM**) [17]

Figure 1: Examples of particle size range of ordinary portland cement (OPC), more conventional supplementary cementing materials (SCM), and nanomaterials.

In the following sections, brief literature reviews on supplementation of the most common nano particles in cementitious materials are provided, and their functionalization and treatment importance is discussed.

Nano-Silica (NS) Supplementation

Nano-silica (NS) is the most widely studied nanomaterial in concrete research due to its cheaper synthesization costs (compared to most other nano-sized particles) and possibly, its chemical composition similarity (very high silica content) to (conventional) silica fume. Silica fume and nano-silica both have spherical shapes with micron-level and nanometer-level particle size distributions, respectively. Micro-silica (silica fume) are distinguished where a high fraction of the silica particles are in micrometer range or the specific surface area is lower than 35 m^2/g. Particle sizes smaller than 20 nm were reported to take slightly more angular shapes and smaller particle size distributions caused aggregation of nano-silica and large differences between particle distribution measurement techniques such as dynamic light scattering and electron microscopy [24]. Various synthesization methods affect the aggregation as high-temperature exposure during synthesization led to clustering (welding/sintering) of the particles [24]. Similar to silica fume, nano-silica takes part in pozzolanic reactions and reduces the portlandite content in the cement pore solution. Apart from the filler and nucleation effects for cement hydrates, NS with participation in the pozzolanic activity generates more C-S-H gels in longer periods leading to denser/stronger cement pastes. Due to the spherical shape of the colloidal nano-silica particles in the cement pore solution and their low aspect ratios, a larger replacement dose may be required to achieve same strength values when compared to finer nano particles with larger aspect ratios. Use of chemical admixtures is essential in proper dispersion of NS specially when supplied in solid forms. NS is mostly procured in solution in concrete research and $^{water}/_{binder}$ ratio must be adjusted to account for the solution's water. Various mixing sequences and admixtures percentages are reported in literature. For instance, Rupasinghe et al. [25] gradually added one-third of NS solution-water mix and one-third of superplasticizer-water mix to the cement in a mortar mixer followed by one minute of mixing. They added the other two thirds in similar manners with a consistent $^{water}/_{binder}$ ratio of 0.3. Their measured isothermal calorimetric curves showed the rate of hydration heat usually remained higher with increase in NS dosage from 4% to 12% (by weight of cement). They used solid NS to superplasticizer (polycarboxylate ether-based) weight ratios of 6.3, 8.4, 9.1 in pastes with 4%, 8% and 12% NS replacements, respectively. Cement pastes with 8% NS replacement exhibited the best performance based on the smallest volume fraction of capillary pores and the largest compressive strength. This was a consequence of efficacy of NS dispersion and their availability to instable portlandite forming more C-S-H gels.

Effect of replacement dose of NS on the mechanical properties have been studied extensively. Wu et al. [26] evaluated mortar mixtures composed of sand (size $\leq$ 2.36mm), portland cement, silica fume, nano-silica, and a polycarboxylate-based superplasticizer. In all the mixtures, the $^{water}/_{binder}$ ratio was 0.18 and the percentages of cement replaced by silica fume was 20%. Nano-silica replacement doses were 0.5%, 1%, 1.5%, and 2% with NS to superplasticizer weight ratios of 0.25, 0.5, 0.75, and 1, respectively. Mortars with 0.5% to 1.5% NS demonstrated higher compressive and flexural strength than the control and 2%-NS-replaced specimens.

Carbon Nano-Tube (CNT) Supplementation

As opposed to the spherical shape of nano-silica, carbon nano-tubes (CNT) possess 1D structures with large aspect ratios that lie between graphene oxides (and graphene) and micro-sized fibers. CNTs are reported to accelerate cement's C_3S hydration but have a high tendency for agglomeration if not functionalized. When CNT was acid-etched, its replacement in cement pastes led to contradictory results in literature. Defects in the CNT structure with broken carbon covalent bonds plus end caps of the tube are potential sites for attachment of carboxyl (-$COOH$), carbonyl (-$\overset{|}{C} = O$) and hydroxyl (-OH) functional groups giving rise to superior dispersion of CNT in cement pore solution. But since CNT takes part in the cement hydration, a reduction in tobermorite (a C-S-H hydration product and major contributer to the paste strength) may follow. This, together with factors such as types, exposure times and ratios of functionalization acids and dispersion surfactants, are the predominant reasons for the contradictory results on mechanical properties among various studies [27]. Excessive acid exposure may damage the CNT structure or reduce the aspect ratios.

Polycarboxylate-based superplasticizers are reported the only category that is compatible with CNTs [19]. Per Collins et al. [28], other categories of the surfactants are not compatible.

Graphene Nano-Platelet (GNP) and Graphene Oxide (GO) Supplementation

Possessing large lateral sizes, 2D graphitic flakes such as graphene nano-platelets (GNP) could be valuable additions to civil cementitious materials specially when durability, particle shielding or thermal/electrical conductivity are of contrasting importance. Du et al. [29] examined influence of GNP at a certain range (0.5%, 1%, 1.5%, 2% & 2.5%) of replacement of cement on pore size distribution, mechanical properties (compressive strength, splitting tensile strength, and static and dynamic moduli of elasticity), resistance to chloride penetration, and water penetration in concrete. While GNPs with higher aspect ratio were reported more efficient in water sorption, the GNP with an intermediate aspect ratio of 215 was used in the study. They used a consistent weight ratio (1.625) of GNP to Darex Super 20 superplasticizer (naphthalene sulfonate-based) in the mixtures. As in other studies, their results indicated certain replacement doses of GNP yielded more favorable outcomes. For instance, the concrete specimens with 1.5% GNP replacement had the most significant reduction in water penetration depth (80% reduction) when compared to control samples with no GNP. A replacement of up to 1% did not result in large reductions. They compared the 1.5%-GNP-replaced samples with another study with 3.5%-replaced-nano-silica samples that had lower reduction in water penetration depth. They ascribed the more favorable occurrence in the former to platelet form of GNP as opposed to spherical shape of nano-silica while no comment on the effects of the type and dosage of the superplasticizers was made. The smallest chloride penetration depth was observed on samples with 1.5% GNP replacement. Samples with larger GNP additions were reported more viscous while it was hypothesized they could result in a more compact microstructure (or supplier of larger barriers in the microstructure) and lead to further reduction in the chloride penetration depth. In spite of the largest reductions in average pore diameter, average air void diameter and fraction of macro-poles in the study's samples with 1.5% GNP replacement, the mechanical properties remained mostly unchanged. This was imputed to the mostly unaffected porosities among the mixtures with various GNP doses. Acid-etching was reported ineffectual in dispersion of GNP due to poor bonds between GNP and cement hydrates [27].

Graphene oxide (GO) as a 2D material can be produced by oxidation and subsequent exfoliation of graphite flakes. Compared to the case of acid-etched CNT in which carboxyl (-$COOH$) and hydroxyl (-OH) functional groups attach to the CNT's surface (due to exposure to acids) [30] or plasma cleaning [31] and electrostatically repulse the CNT whilst significantly improving the dispersion, GO inherently contains carboxyl, hydroxyl, and epoxy functional groups during its synthesization. Apart from the filler benefits of GO, the carboxyl groups can chemically react with the calcium silicate hydrate (C-S-H) products of cement hydration and result in more compact GO-cement composite microstructures and enhancement of mechanical properties. The *relative* dispensability of surfactants in dispersion of GO stems from the attached functional groups that inherently assist the dispersion. Additionally, as a result of significantly larger surface area of GO (compared to CNT) and its aforementioned hydrophilic property, larger water sorption to its surface and frictional resistance between the cement and GO sheets takes place. This concludes a viscous mixture with the workability reducing with increase in the GO's sizes (due to higher frictional interlocking) [19].

Ghazizadeh et al. [32] examined colloidal stability of GO in C_3S paste. Solutions with high pH in the study was prepared by a mixture of GO solutions with either calcium hydroxide solution or alite (C_3S) solution. They concluded GO instability led to their aggregation as a result of a drastic reduction in the functional groups at high pH due to complexation with calcium cations (Ca^{2+} ions produced with the hydration in the alite or cement pore solution). This effect is somewhat similar to the above-mentioned result of acid-etched CNTs in which acid exposure introduces the functional groups to the CNT surface. They additionally suggested another mechanism for the aggregation/instability based on the reaction between hydroxide ions and GO. Furthermore, they questioned the nucleation effect of GO reported in the literature for its large strength contribution in cement pastes. They suggested, as a result of significant reduction of functional groups at high pH (prevailing in the cement pastes, for instance), various chemical functionalizations may be essential to reduce GO aggregation.

Li et al. [33] evaluated cement pastes with 0%, 0.02%, 0.04%, 0.06%, and 0.08% of ordinary portland cement (OPC) replaced with GO as well as C_3S pastes with 0% and 0.02% of C_3S replaced with GO. The increase in the rate of hydration heat release in GO-cement pastes was more pronounced in the second peak and this was attributed to more effectiveness of GO in C_3A hydration (by nucleation effect) than in C_3S. The rate increased with the GO dosage. The nucleation effect of GO was not determinant in the GO-C_3S pastes since the control OPC paste and the pastes with 0.02% GO replacement did not differ in the generated hydration heats. They further reported the 0.02%-GO-replaced cement pastes displayed the highest electrical resistivity suggesting at higher GO doses, more available carboxyl groups facilitated the ions diffusion. Similar to the studies of other nanomaterials, the results showcased an optimum range of GO replacement dosage within which maximum flexural strength and compressive strength are achieved; In the study, the compressive strength of the GO-cement consistently increased with GO dosage while it remained unchanged between pastes with 0.06% and 0.08% GO replacements; Pastes with 0.02% GO experienced the peak in the flexural strength due to agglomeration of GO at higher doses. Nucleation effect of GO is discussed by Lv et al. [34] through formation of thick column-shaped hydration products such as *AFt* (alumina, ferric oxide, tri-sulfate), *AFm* (alumina, ferric oxide, mono-sulfate), *CH* (portlandite or calcium hydroxide or $Ca(OH)_2$), and *C-S-H* chemically attached to the GO sheets at the functional group sites. Some of the thinner crystalline hydration products populated on the surface of the columns producing flower-shaped structures. These flower-shaped bundles were reported to occupy the pores and cracks in the paste with time and strengthen the paste as fillers and pore crack bridging assistants. Cui et al. [35] questioned this mechanism and suggested the flower-shaped bundles are calcium carbonates and result of poor SEM sample preparation hence carbonation of cementitious hydrates.

Qin et al. [24] reported the maximum 28-day mortar compressive strength increase (by 126%) in specimens with 0.5% replacement with GO (based on total mass of mortar) together with microwave curing (5 minutes). The effect of microwave irradiation coupled with dispersion in various solvents such as chloroform (a source of chlorine species such as Cl and CCl_3 upon irradiation) and N-Dimethylformamide (DMF) was investigated by Okimoto et al. [36]. They showed that covalent bonds formed between Cl atoms and two sides of the graphene sheets when graphene in chloroform was subjected to microwaving. In contrast, graphene in DMF solution did not exhibit dispersion after the microwave irradiation and was unstable. Graphene in DMF shows very high stability under ultrasonication. They attributed the high stability of graphene in chloroform to synergistic effect of microwaving on both decomposition of chloroform (and consequently, bond of the products with graphene) and high temperature mobilization of the solution.

Kang et al. [13] reported optimum GO replacement doses of 0.05%, 0.1% and 0.01% from compressive, flexural and tensile strength tests on mortars, respectively. The corresponding increases in the 28-day compressive and flexural strength values with respect to control samples were 32%, 20%, respectively and the corresponding 7-day tensile strength increase by 35%.

Improvement of mechanical properties (up to 77.7% and 37.5% in 28-day compressive and tensile strengths, respectively) and hydration acceleration (up to 12% at 28 days) of mortars modified with GO doses up to 0.1% were attributed to increase in the hydrogen bonds between the GO's oxygen functional groups and the paste's C-(A)-S-H phases plus increase in intercalated water between GO sheets in samples with well-exfoliated singular GO flakes [37]. This was suggested per gradual intensification of O-H and C=O bands in the transmission FTIR spectra in samples with increasing GO contents up to 0.1%. Decay in mortar mechanical properties with GO content of 0.5% was reported due to aggregation of the GO flakes. Same researchers suggested an intermediate GO reduction (with incorporation of an oxygen-reducing agent [hydrazine] at 0.2% of GO weight into the GO solution for 15 minutes and prior to addition of cement and sand) further enhanced the mechanical properties (83.7% and 45% in 28-day compressive and tensile strengths, respectively) [38]. This intermediate reduction range was suggested to be beneficial since excessive reduction would yield to aggregation of reduced GO sheets due to attached oxygen functional groups reductions while a minimal reduction (retaining high density of oxygen functionalities) was suggested to cause frictionless flow of water molecules on the GO sheets hence water instability and decay in the bonds in the cementitious paste. Refinement of the paste microstructure by GO supplementation has been reported by reduction of the capillary pore volume (e.g., by 32% [39]) and drying shrinkage (e.g., by 33% [40])).

Boron Nitride (BN) and Boron Carbide (B_4C) Supplementation

Boron nitride (BN) has been studied in literature due to such properties as usually higher thermal conductivity and lower electrical conductivity (when compared to graphene) and lubrication. The former is one of the reasons for application of BN in the ceramics industry. BN nanomaterials are potential candidates for supplementation in a composite where heat sink/dissipation is desirable. BN exists in either an amorphous form or one of the crystalline hexagonal (hBN), cubic (cBN) or Wurtzite (wBN) structures with most of the studies on hBN that has a similar 2D hexagonal form to graphene sheets. hBN nanosheets exhibit instability in water unless functionalized. Lin et al. [41] reported sonication-assisted dispersion of hBN in water stable. They attributed this to the solvent (water)'s polarity effect plus hydrolysis (functionalization by -OH groups) of hBN sheets under sonication. They reported stable hBN aqueous solution upon addition of a strong base after sonication while addition of acid led to precipitation of hBN nanosheets overnight. Their results suggest sonication of pristine hBN in water is essential in the nanomaterial supplementation in the cement matrix whilst the basic environment of the cement hydrate is not expected to be deleterious from the perspective of hBN's homogeneous dispersion only (affinity of the functionalized hBN with cement hydrates is another determinant factor).

Ribeiro et al. [42] evaluated 0.25%, 0.5% and 1% addition of hBN and molybdenium (IV) sulfide (MoS_2) into a commercial liquid epoxy and reported such improvements as increases of up to 203% in thermal conductivity and up to 95%, 60% and 58% in tensile strength, ultimate strain and elastic modulus, respectively when compared to properties of the epoxy polymer alone. Glass transition temperature and viscoelastic storage modulus improved as well. These appealing results of hBN incorporation could be studied and utilized in fiber-reinforced polymer (FRP) applications in concrete infrastructures when exposure to high temperature is a concern. Inclusion of higher doses of hBN (up to 60%) in the composite has been imparted favorable with higher thermal conductivity and heat dissipation capabilities but it compromises viscosity of the mix and mechanical properties largely.

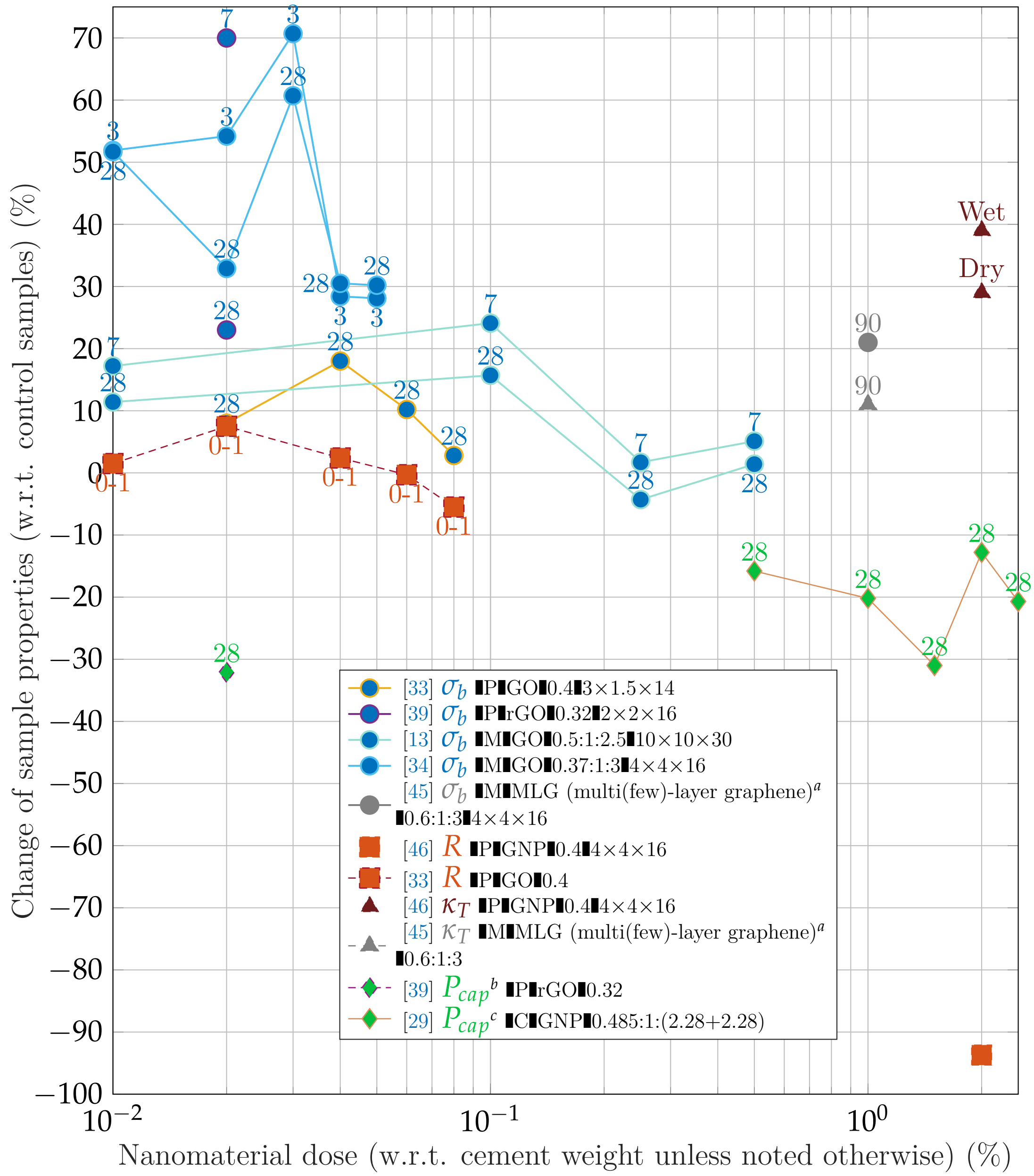
Boron carbide (B_4C) in concrete wall and roof members has been proposed for shielding against radiation generated by subatomic collisions. It often has particle size distributions at micron level but has been utilized in metal matrix composites, abrasives and defense industry. Boron atom has a high neutron absorption capability removing radiated slow-thermal neutrons with desirable low gamma rays generation. As a result of its brittleness in its pure form, compound such as boron carbide (with a high concentration of boron) have been incorporated into the mix [43]. Heavy-weight aggregates (with their pure mineral specific gravity $\gtrsim 4$) and boron ores differentiate radiation-shielding concrete from conventional normal-weight concrete. Prestressed concrete reactor vessels require higher thermal stability due to thermal fluctuations to more than 70 °C [20, p515-518] and geopolymers containing boron minerals and heavy-weight aggregates are viable substitution options.

Literature Survey Summary

A literature survey of the effect of 2D nanomaterials on several properties of civil cementitious materials is shown in Figures 2 and 3. A similar comparison on CNT was provided elsewhere [19]. Inconsistent results on these properties eventuate from various testing protocols, nano-scale morphology, dispersion and affinities of the nanomaterials with cement hydrates, preparation methods, and aggregate sizes, shapes and percentage in the mix (for mortar/concrete samples) hence evolution of distinct interfacial transition zones. One important observation is that promising improvements in the paste reported in literature may not translate into the same desirable results in concrete/mortar due to the additional heterogeneity. As shown, an increase beyond a certain substitution dose often does not result in improvements in mechanical (and durability) properties. As expected, electrical and thermal conductivities are usually elevated with increase in the graphitic nanoparticles content. Improvement of thermal and electrical conductivities requires a sufficiently high supplementation percentage of the nanomaterials (typically more than 1-5 wt.% of the matrix/mixture in order to obtain noticeable changes; similar to reported literature in composites with low-conductivity matrix utilized in aerospace and mechanical engineering applications such as polymer matrix composites [44]) that may compromise mechanical properties and durability of the cementitious composite. Cementitious materials modified with fibers/reinforcements with macro-/micro- meter longitudinal dimensions such as steel fiber, carbon fiber and carbon nanofiber (CNF) could result in more desirable mechanical properties due to more efficacy in crack bridging mechanisms but reported durability and porosity improvements of specimens modified with nanomaterials could potentially contrast them, making them viable substitution options as their synthesization costs reduce.

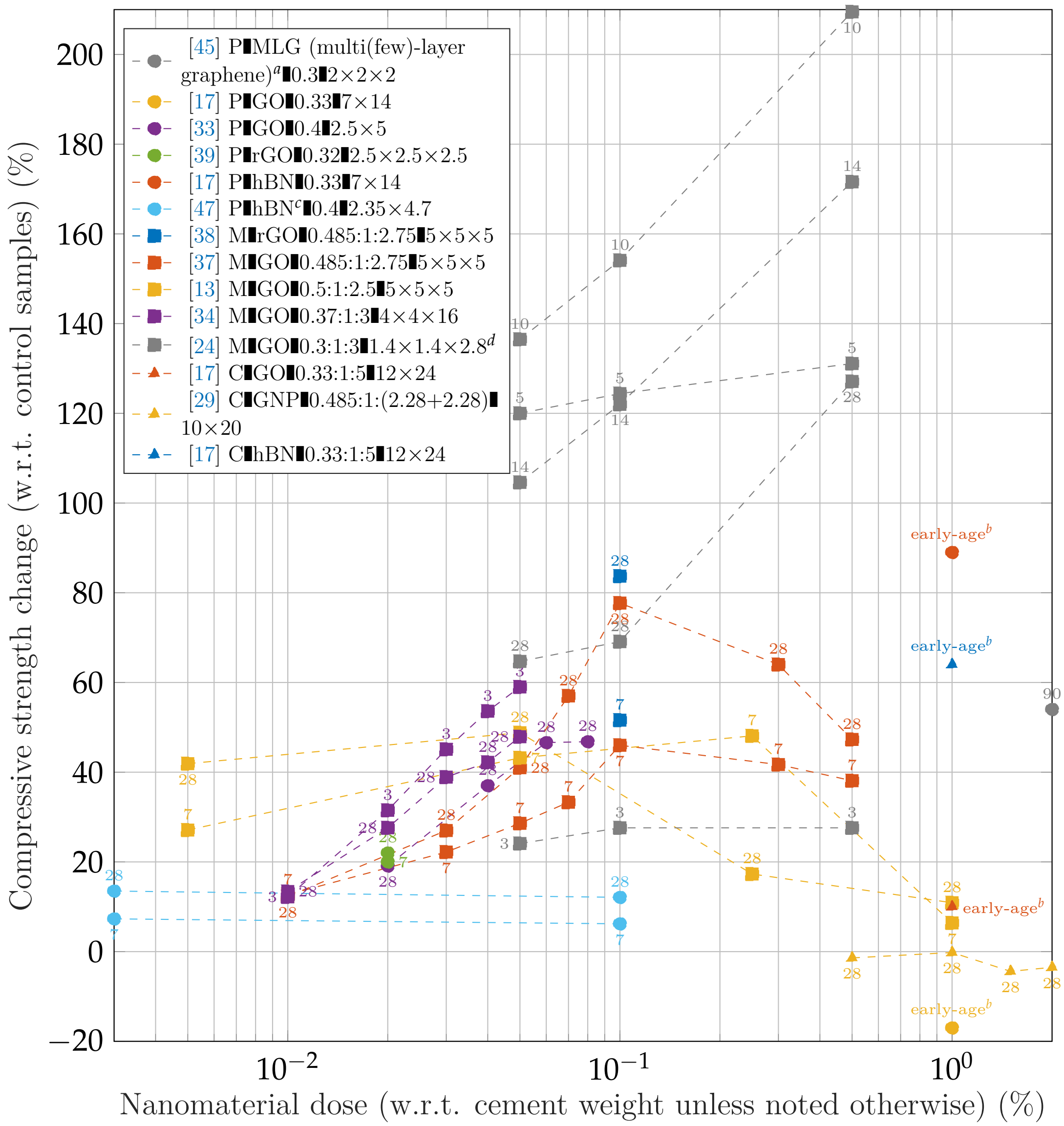
Conclusions

In this paper, a brief literature study of effects of several nanomaterials in civil cementitious materials was presented. These materials could potentially tweak the structure of multifunctional concrete and improve energy management, structural health monitoring, self-healing, and radiation shielding. With the increasing focus on energy harvesting and management in the past decade, they can be utilized in development of thermoelectric concrete in which a form of electrical or thermal gradient can furnish a gradient in the other one presenting a smart clock that can be switched depending on the environments of interior and exterior of a building envelope. Addictive manufacturing of concrete is another application where nanomaterials can excel at.



Notes: Legend naming convention:
[reference] σ_b(flexural strength) or R(electrical resistivity) or κ_T (thermal conductivity) or P_{cap}(capillary porosity) data comparison ▮P(paste), M(mortar), C(concrete)▮nanomaterial▮water:cement or water:cement:aggregate(fine aggregate+coarse aggregate) ratio▮sample size (width×depth×length) [cm^3] (if applicable).
Values next to markers represent sample age [days].
[a]Dose based on total volume of composite.
[b,c]Capillary pores reported: 10nm-10μm and 50nm-10μm, respectively measured by MIP.

Figure 2: Comparison of changes of flexural strength, electrical resistivity, thermal conductivity and porosity of samples modified with nanomaterials reported in literature.



Notes: Legend naming convention:
[reference] P(paste), M(mortar), C(concrete)▮nanomaterial▮water:cement or water:cement:aggregate(fine aggregate+coarse aggregate) ratio▮sample size (width×depth×length or diameter×length) [cm^3].
Values next to markers represent sample age [days].
^{a}Dose based on total volume of composite.
^{b}Test age not provided.
^{c}Smaller and larger doses represented supernatant of centrifuged hBN solution and non-centrifuged hBN solution, respectively.
^{d}Reference mentioned doses were based on total weight of composite that would result in doses of 0.22%, 0.43%, 2.5%, respectively, w.r.t. cement weight. Strength comparisons shown here were between microwave- untreated and treated samples cured at room atmosphere. The specified sample sizes in *inch* were likely in *mm*. This study's data is not reliable.

Figure 3: Comparison of compressive strength changes of samples modified with nanomaterials reported in literature.

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Seamless Architecture: Design and Development of Functionally-Graded Green Materials for Building Construction

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ABSTRACT

Functionally-graded materials (FGM) can be found in many natural structures such as bones, which have been studied in biomimetic research. Their varied properties, behavior, and application have been replicated in the design of synthetic materials and systems. FGMs offer promising solutions in the development of building components where multiple programmatic requirements need to be met and economy of means matter most both in the production processes as well as in performance.

Conventional buildings account for almost 40% of carbon dioxide emission including energy spent to produce materials and components, and energy used to maintain and occupy them. Despite the complex mechanical joints or chemical bonds uniting materials or building components, a great amount of heat is lost through inefficient details that cannot guarantee impermeability even in presence of sufficient insulation. We need to rethink how materials/components are produced and joined.

We have achieved impermeable, seamless, and progressive transition from ceramized geopolymer (GP) concrete with structural properties, to transparent glass. GP is an alternative to portland cement with multiple advantages particularly in response to the environmental concerns and sustainable practices with less embodied and operational energy. A green FGM was engineered using compositional gradients from 95% GP to 100% glass. This paper shares our observations of effective features that influence the quality and material properties of FGMs made of binary blend of GP and glass powder. These features include the influence of sintering process, GP and glass powder chemical composition, exposure conditions, and thickness of different layers. The results of our observations were used to produce a larger specimen, a 400mm column, of functionally graded composite material, made of 21 layers of binary blend of GP and glass powder.

1. INTRODUCTION

Buildings contain thousands of components and materials, which are brought together using different mechanical joints or adhesives. Depending on the role and location of these components or materials the joint must address multiple requirements such as air-tightness, water-tightness, sound proofing, load bearing, motion or equilibrium. Joints may be parallel to a wall plane or between layers within the wall itself. Because mechanical or chemical bonds cannot guarantee a sealed condition, there is most often the need to provide added thermal and /or acoustic insulation, and sealants to protect against water or air seepage.

As a result, in contemporary architecture, we have a staggering number of joint and numerous trades involved that need to be coordinated during construction and maintained regularly in the lifetime of a building. The added costs in production and labor, and certainly the wasted energy both in production and in use throughout the life of a building are symptoms and cause of a pattern, a process, and certainly products that are no longer sustainable. This complexity and waste cannot be sustained in the building and construction industries, which are responsible for a massive source of CO_2 emission in the US and the world.

It is time to rethink our building conventions, to simplify them, and to inform them of the advancements in material science and technologies of manufacturing and construction. This project presents an interdisciplinary approach for the design and development of novel materials to simplify and strengthen not only the construction industry, but to present unique architectural details and experiences.

Furthermore, cement-free alternatives have been proposed recently for concrete industry in response to the environmental concern regarding the production of portland cement (PC) (Mehta (2001), Shi et al. (2006), and Provis (2014)). Alkali-activated binder is one of the promising alternatives to PC which forming through a chemical reaction between the high alkaline solution and aluminosilicate source precursor such as slag or fly ash. In the current work, alkali-activated binder is used as a geopolymer (GP) material.

Our team has designed and developed functionally graded materials (FGMs) that reduce carbon footprint during production and in use. We are presenting in this paper a composite material that enables us to achieve higher structural strength where the building needs to bear loads, and by changing the ratios of the components to achieve thermal and acoustical insulation where needed, impermeability where needed and transparency where picture windows are desired. We can transition seamlessly from GP concrete to glass with clear boundaries between these materials or along any given dimension in length or depth of a single wall to address functional, optical, experiential, and structural requirements for construction of a variety of structures for applications in the arts, industrial design, building construction, aerospace research, and architecture.

2. EXPERIMENTAL PROCEDURES

2.1. Solid materials

GP paste in this study was alkali-activated fly ash (AAF), and alkali-activated fly ash-slag (AAFS) binary pastes. The solid materials used in this study were: a class F fly ash (FA) meeting ASTM C618-15 requirements, a grade 100 ground granulated blast furnace slag (S) meeting ASTM C989M-12, partially-fused metabasalt with uniform grading, soda lime glass chunks and glass sheets. The composition and physical properties of the raw materials are shown in Table 1.

Four different GP mixtures (three AAF together with an AAFS ($(S/FA)_{vol}$ = 10%) were designed according to the previous studies (Hojati and Radlińska (2017)) and tested in this research. All pastes were mixed following ASTM C 305-13, where the dry powder (fly ash or a blend of fly ash and slag) was added into an aqueous activator. The cementitious (powder) materials were mixed using three activators with different modulus (n = $(SiO_2/Na_2O)_{mol}$ = 1.60, 1.10 or 0.94) and pH values (13.7, 14.44, or 14.63), as shown in Table 2. The liquid (activating solution) to solid binder (fly ash + slag) volumetric ratio of all mixtures was 1. All of the GP were heat-cured for the first day after casting, at 60°C.

Alkali activators were prepared following the method outlined in Hojati et al. (2016). Properties of activators are shown in Table 2. GP1 activated by using a commercially available aqueous sodium silicate while GP2, GP3, and GP4 were activated by the aqueous sodium silicate mixing with either 6 M or 10 M sodium hydroxide (NaOH) solution. The commercial aqueous sodium silicate consisted of 18.0% mass Na_2O, 28.8% SiO_2 and 53.2% H_2O, and had specific gravity of 1.6 g/cm^3 at 20°C, and pH = 13.70. The mass ratio of sodium silicate to sodium hydroxide solutions for GP2, GP3, and GP4 mixtures were maintained at 2.0. GP3-B in Table 2 represents the addition of fine partially-fused metabasalt to the GP3 powder. Basaltic sand was used to minimize the cracking in the GP-rich layers. After demolding GPs, they were dried in the furnace at 200°C for 4 hours, then ground to the specific sizes (sieved by sieves # 60 and 140), and according Table 3 classified in three grades, Coarse-size GP (C-GP) with particles larger than 250 µm, Medium -size GP (M-GP) with particles coarser than105µm and finer than 250 µm, and Fine-size GP (F-GP) with particles smaller than 105 µm.

Glass chunks were also ground and sieved by sieves # 60 and 140. The gradation of glass powder is displayed in Table 3. The glass chips were also prepared by breaking glass sheets and used at the very top layer of the specimen. To prevent contamination, the glass sheets and chunks were perfectly washed and cleaned up with isopropyl alcohol 70% before grinding or crushing process.

Table 1. Oxide compositions (mass %) of FA, and GGBFS powders

Oxides	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	Na_2O_{eq}	LOI	Sp. Gr.
Fly ash	46.69	22.44	4.99	19.43	1.04	0.76	1.74	2.00	2.64
Slag	30.80	11.45	47.50	2.26	3.65	3.03	0.27	2.56	2.85
Glass chunks	63.8	14.4	4.4	-	-	-	-	-	-

*Note: Sp.Gr. is the specific gravity of each powder

Table 2.Activating solution properties and mixture design of GPs

GP	Mixture ID.	Activator Composition		FA	S	Partially-Fused Metabasalt
		pH	n = (SiO_2/Na_2O) molar-based			
AAF	GP1	13.70	1.60	100%	0%	No
	GP2	14.44	1.10	100%	0%	No
	GP3	14.63	0.94	100%	0%	No
	GP3-B	14.63	0.94	100%	0%	Yes
AAFS	GP4	14.63	0.94	90%	10%	No

Table 3. Gradation of GP and Glass powders

Size range	GP	Glass Powder
> 205 µm	C-GP	C-G
105 µm - 205 µm	M-GP	M-G
<105 µm	F-GP	F-G

2.2. Preparation of samples

As plaster is fire resistant, plaster molds were cast and used for this work. For the first part of this research, small samples (different sizes) were cast to adjust the sintering process; then in the next part which studied the influence of using different GPs (Table 2) for making FGM, five 50×50×50 mm (2×2×2 in) cubes were cast, for each cube, one of the GPs listed in Table 2 was used. Each cube was made of three layers of different binary blends of GP and glass powders. The gradation and proportion of GP to glass powders for each layer is shown in Figure 1. For GP3-B, 20% of GP was replaced by basaltic sand at the bottom layer to restrict the cracking and lower the shrinkage of GP-rich layer.

In the next parts of this research, a binary blend of GP1 and glass powder was used to make 100mm and 400mm columns of FGM. The content of the glass was gradually changed throughout the length of the column from 5% to 100% and there was a layer of glass chips at the top.

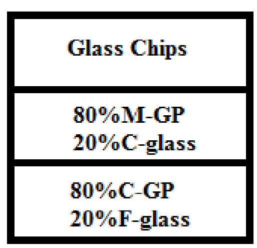


Figure 1. The gradation and proportion of GP and glass powders in a 3-layers of 50×50×50 mm cubes

For each layer, the powders (GP, basalt and glass) were well mixed together before casting the column, then they were added into the mold, and well compacted, layer by layer. Afterward, the molded powders were fired in the furnace up to 850°C according to a specific firing schedule shown in Figure 2 (Shelby (2005)). A seamless material was formed with functionally graded properties through this process. Figure 3 displays different processes of preparing FGM columns.

To explain the observation of this study, the coefficient of thermal expansion (CTE) was also measured using a dilatometer (DIL 402 C, Netzsch, Selb, Germany).

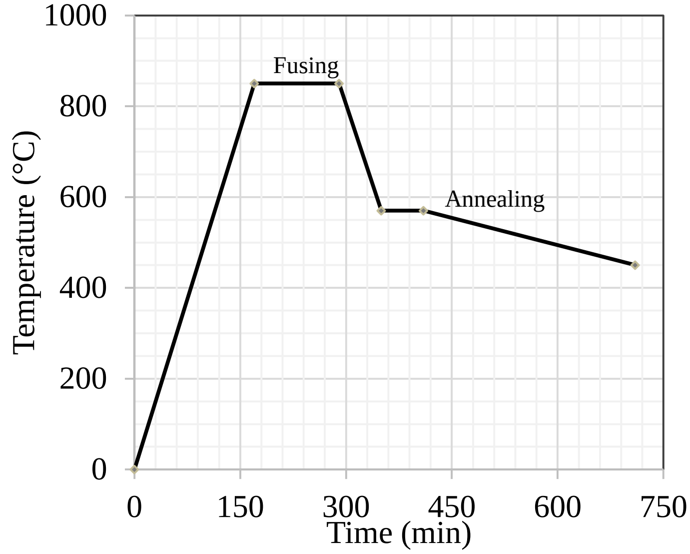
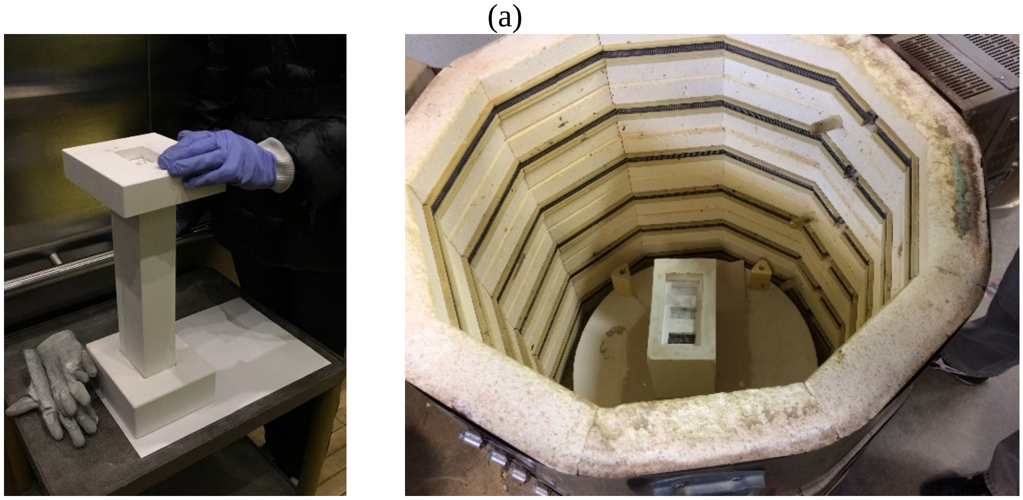


Figure 2. Firing schedule used for fusing different layers and powders

(a)



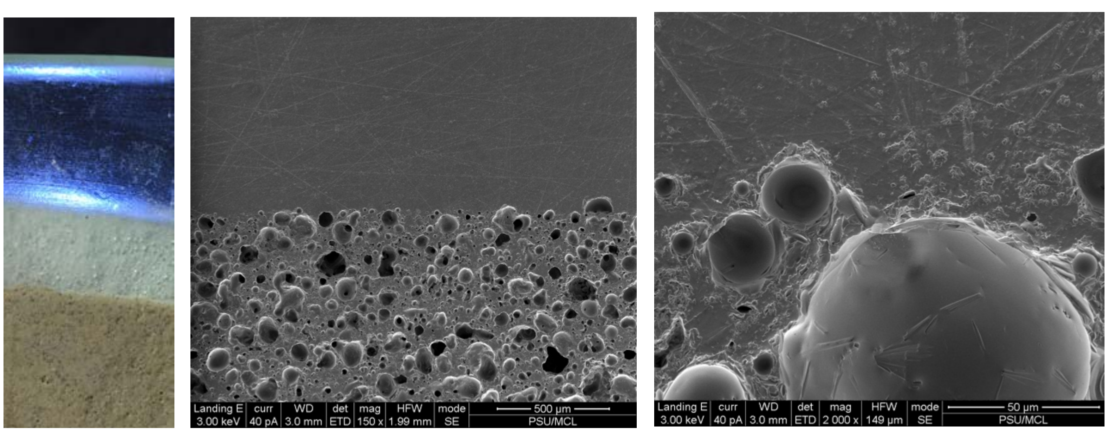
(a) (b)

Figure 3. Preparation process of FGM (a) pouring the right combination of materials into the plaster molds (b) placing the molds into the furnace

3. RESULTS AND DISCUSSION

3.2. Preliminary experiments to set a sintering process

To fuse the opaque ceramic to transparent glass without using the third element, materials were fired at high temperatures. Various samples were prepared and tested (Nazarian et al. (2017)). Where GP, which is obtained at room temperature, is fired at temperatures above 600°C, it transforms into an advanced ceramic material with improved properties that can seamlessly interface with dense glass. Figure 4 shows a pictures of 2-part FGM. This sample was made by placing a transparent sheet-glass in contact with GP in powder form and firing them together to form a ceramic-glass structure with the desired optical and structural properties. Figure 4 (b-c) display the Scanning Electron Microscopy (SEM) of the interface between a ceramized GP (on the bottom) & glass (on the top). Different firing schedules and preparation procedures were used to achieve the best results. It was observed that the transparency of glass and development of cracks are highly dependent on the sintering process. The rate at which the material is heated up, and how slowly it is cooled down are also important variables that affect the vitrification and annealing of the glass components in the specimen. The firing schedule (sintering process) which was used in the final experiment to make the FGM samples shown in Figure 2. After pouring each layer of glass powder and GP with different proportions into the plaster mold, the mold was placed into the furnace and fired up quickly to 850°C, and kept at that temperature for two hours, when the particles of GP and glass in the composite material were fused together and ceramized. Then the specimen was cooled down to 570°C, at 4.7°C/min cooling rate, and held at 570°C for 1 hour, followed by the annealing stage when the formed object was cooled down from 570°C to 450°C very slowly, in a duration of 5 hours, to relieve the residual internal stresses that were introduced during the manufacturing process and avoid cracks from forming. Finally, the furnace is turned off and allowed to cool to room temperature.



(a) (b) (c)

Figure 4 (a) Interface between GP (bottom) and glass (top), (b, c) Scanning Electron Microscopy (SEM) showing Microstructural details of the interface between geopolymer (on the bottom), and soda lime glass (on the top) after firing at 850°C
Note: Figure 4c zooms into a portion of 4b

3.2. Preliminary results of different GPs

The FGM cubes were prepared and fired according to Figure 2. The samples were set aside till they cooled down to room temperature. Then they were demolded. Figure 5 displays the FGMs made of using different GPs in powder form. All of these FGMs, were made of three layers of different combinations of glass powder, GP, and basalt. The soda lime glass with low iron was used for this part. All of the specimens formed a clearly visible seamless interface from ceramic to glass. It is notable the FGM prepared by using GP1 formed a flawless ceramic with no visible crack. However, other GPs formed crack, and among them, GP2 formed the most noticeable cracks. Comparing GP3 and GP3-B shows that addition of partially-fused metabasalt to GP can somehow prevent cracking. Furthermore, addition of slag to GP3 (to form GP4) lowered the cracking remarkably in ceramic part of FGMs.

To fuse the geopolymer and glass powder together, they should be fired and heated up at the very high temperature (in this experiment up to 850°C). In order to achieve the best fusion between the initial materials at such a high temperature, their CTE should be close or similar to each other. The difference between CTE of GPs and glass after firing up to 850°C would result in sever cracking of ceramics as observed in Figure 5. Previous studies showed that the properties of GPs are highly dependent on the properties of alkaline solution. According to previous studies (Shelby, J.E. (2005)), increasing the alkali content of activating solution (Table 2) in GPs resulted in a higher CTE. The CTEs of different GPs (made of metakaolin or fly ash activated with different activating solutions) and soda-lime glass were measured and shown in Figure 6. In general, the results indicate that CTE of soda-lime glass and GP are close to each other and there is a slight difference between them at higher temperatures (> 400°C). The best match between CTEs of GP and glass was observed for the GP1, which is made of the sodium-silicate solution of n=1.60 and pH=13.7 (i.e., m=0.2, r=1.65).

These FGM cubes were preliminary experiments to find the most compatible GP, which can be used with least amount of cracking, resulting in the best seamless interface between different layers.

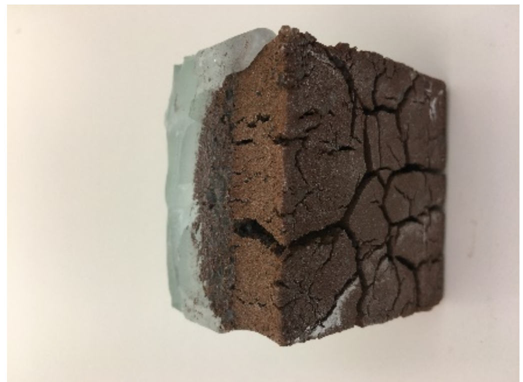
3.3. Preliminary experiments to adjust the chemical composition of glass, layering thickness and exposures conditions

After doing the preliminary experiments to figure out the best sintering process and most promising GPs, we focused our attention to the influences of the glass composition (low-iron soda lime glass versus ordinary soda-lime glass powder), the exposure conditions (which layer is exposed to the air), and the gradual change of material composition and ratios form 100% GP to 100% glass on the quality of the resultant FGMs. Table 4 to Table 6 show the effect of each variable on the 100 mm-FGM columns, which had either 5 or 6 layers of different proportions of GP to glass powder. For all of the columns, GP1 was used for the structural part, and sintering process shown in Figure 2 was applied.

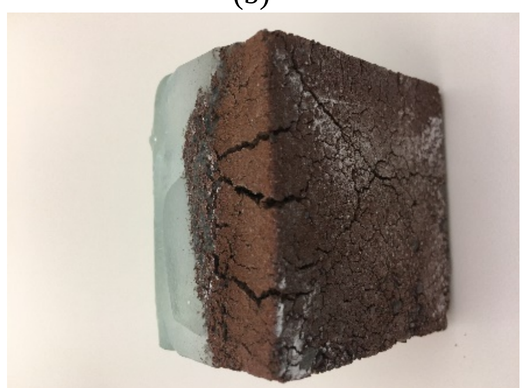
Table 4 illustrates the 100 mm-FGM column, where the low-iron glass powder was used, the glass chips were exposed to the air (top layer), and the GP content was gradually changed from 20% (bottom layer) to 0% at the top layer in 5%-glass powder increment. It is notable that the GP and glass particles were flawlessly fused together at high temperature and formed a dense and uniform FGM.

Table 5 displays the results of 100 mm-FGM column made of soda-lime glass, while the glass chips were exposed to the air again, but GP content changed from 100% at bottom layer to 0% at the top layer (in 5 layers of glass-powder increments). It was observed that 100% GP layer shrunk and noticeable cracks propagated through the specimen, however, GP1 was used (which exhibited almost similar CTE to the soda lime glass). For the internal layers with binary mixture of GP and soda-lime glass powder, a slight expansion in the final products was observed, which gets larger by increasing the glass powder content. Comparison of Table 4 with Table 5 points out the importance of glass powder composition (low-iron soda lime vs. ordinary soda-lime glass) and the change of glass powder quantity between successive layers. The specimen in Table 4 led to a flawless FGM-column without any notable boundary between different layers, which resulted from slight difference between the composition of successive layers or the use of low-iron glass powder. According to Table 5, 100%GP may shrink and crack at high temperature. It was observed that addition of low content of glass powder (5% or higher) in the structural (GP) layers might prevent this cracking.


(a)


(b)


(c)


(d)

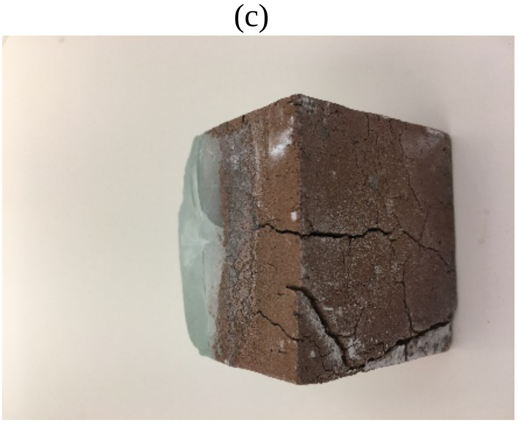

(e)

Figure 5 Picture of different cubes ((a) GP1, (b) GP2, (c) GP3, (d) GP3-B, (e) GP4 made of low-iron glass

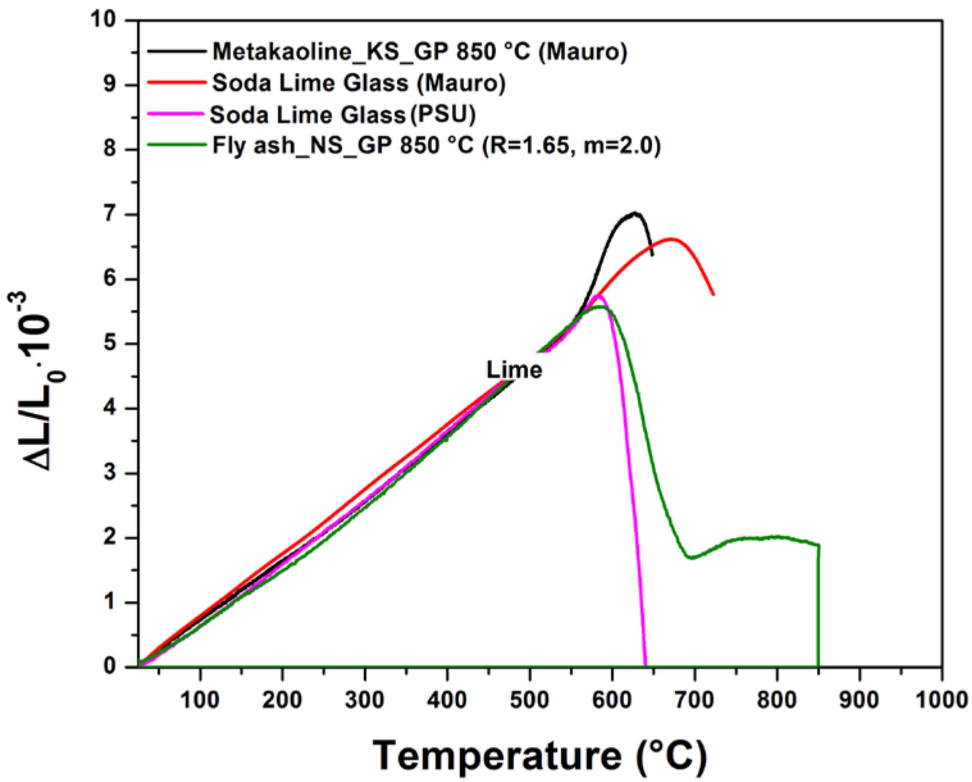


Figure 6 Coefficients of thermal expansion (CTE) of different geopolymers and glass

Table 6 shows the 100 mm-column of soda-lime glass powder and GP, where GP-rich layer (80%GP+20% glass powder) was exposed to the air (top layer), and the very bottom layer is 100% glass chips. In comparison with Table 5, the results showed how the order of layers could influence the final product. In this specimen, the top three layers shrunk and a distinguished boundary formed between layers 3 and 4. There is no cracking in the GP rich layers, which can be attributed to the inclusion of 20% glass powder instead of pure GP layer. To scale up the FGM from small cubes to larger column, there are some considerations which could lead to better resultants (i.e., FGM):

1- Using low-iron glass led to a better product after firing without any considerable volume change (expansion) of glass-rich layers (comparing Table 4 and Table 5).
2- Comparing Table 4 and Table 6, where GP-rich layer is subjected to the air, it would shrink. As such, it would be better to put a low-iron glass as a top layer.
3- To lower the significant volume change between layers, it would be practical to increase the numbers of the layers for a given length of a column and change the material composition in a smaller increment.
4- Using 100%GP may result in cracking at the very high temperature. Addition of small amount of glass powder in GP-rich layers would prevent the cracking due to balancing of the CTEs between different layers.

3.4. Scaling up the size of FGM samples

This section reviews our attempt to scale up the size of samples from small cubes (50mm)

and columns (100mm) to a longer column (400mm). By considering all of the observation from preliminary experiments, a 400mm columns of FFM was cast and fired by applying all of the experiences gained to this point. The column was made of 21 layers of a binary blend of GP and low-iron glass powder followed by glass chips at the very top, exposed to air (layer#21 was located at the top of the mold and exposed to the air during firing process.). The content of glass was gradually changed over the length of the column from 5% to 100%. Table 7 shows the mixing proportion of each layer. The depth of each layer (except layer#21) was close to 20 mm. Depth of layer#21 (the very top layer) was about 38 mm. The column was placed in the furnace and supported by 4 layers of bricks (16 bricks in total) to avoid toppling of the two-part mold that was held steady inside a 2" high plaster base. The sintering process was set according to Figure 2, however, the cooling rate to room temperature was about two days longer due to the fact that the brick layers kept the heat from falling as quickly as desired, but the brick layers supported the mold very well and prevented any plaster-mold from collapsing during the firing process. The only drawback was devitrification of the top layers, particularly where glass chips on the very top could have maintained their transparency if the temperature of the specimen fell as quickly as desired when the furnace was turned off at 450°C. Table 7 displays the final product and shows how the binary of GP and glass were well-fused together. The column is very dense in the bottom layers (GP-rich layers) but it started expanding in the mid-length, the matrix is not very dense, and visible pores and voids were developed in the mid-layers (layer#5 to #15). The largest expansion was seen in the mid-length of the column as it could be observed in Table 7. It was also remarkable that the voids became larger as the trapped air escaped the interior of the specimen toward the glass-rich layer (layer 21).
Further studies are needed to investigate why the upper layers (glass-rich layers) were expanded and led to formation of voids. New sintering processes may need to be engineered for larger specimens. This is an ongoing research and in the next phases, the focus will be on problems that arise as we scale- up and quantify the material properties of FGMs.

Table 4- 5-layer column of functionally graded material made of low-iron glass powder, GP and glass chips, while the glass chip layer was exposed to the air (top layer)

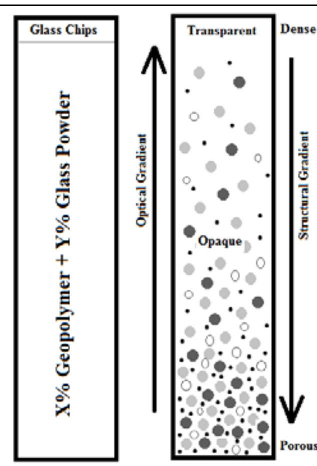
<table>
<tr><th>Layer #</th><th>GP (X%)</th><th>Glass Powder (Y%)</th><th>Glass Chips</th><th>Picture of final product</th><th>Schematic picture of functionally graded material</th></tr>
<tr><td>1</td><td>0</td><td>0</td><td>100</td><td rowspan="5"></td><td rowspan="5"></td></tr>
<tr><td>2</td><td>5</td><td>95</td><td rowspan="4">0</td></tr>
<tr><td>3</td><td>10</td><td>90</td></tr>
<tr><td>4</td><td>15</td><td>85</td></tr>
<tr><td>5</td><td>20</td><td>80</td></tr>
</table>

Table 5- 6-layer column of functionally graded material made of soda-lime glass, GP, and the glass chip, while the glass chip layer was exposed to the air (top layer)

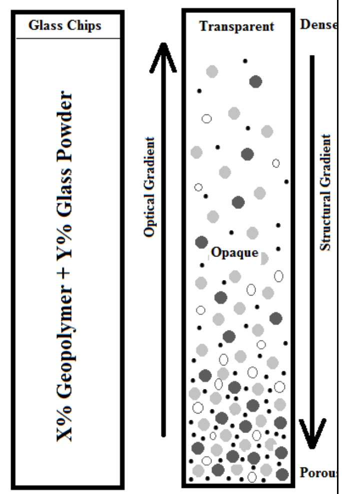
<table>
<tr><th>Layer #</th><th>GP (X%)</th><th>Glass Powder (Y%)</th><th>Glass Chips</th><th>Picture of final product</th><th>Schematic picture of functionally graded material</th></tr>
<tr><td>1</td><td>0</td><td>0</td><td>100</td><td rowspan="6"></td><td rowspan="6">
</td></tr>
<tr><td>2</td><td>20</td><td>80</td><td rowspan="5">0</td></tr>
<tr><td>3</td><td>40</td><td>60</td></tr>
<tr><td>4</td><td>60</td><td>40</td></tr>
<tr><td>5</td><td>80</td><td>20</td></tr>
<tr><td>6</td><td>100</td><td>0</td></tr>
</table>

Table 6- 5-layer column of functionally graded material made of soda-lime glass, GP, and the glass chips, while the glass chip layer was exposed to the air (top layer)

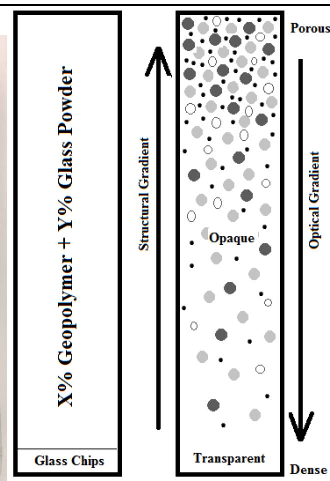
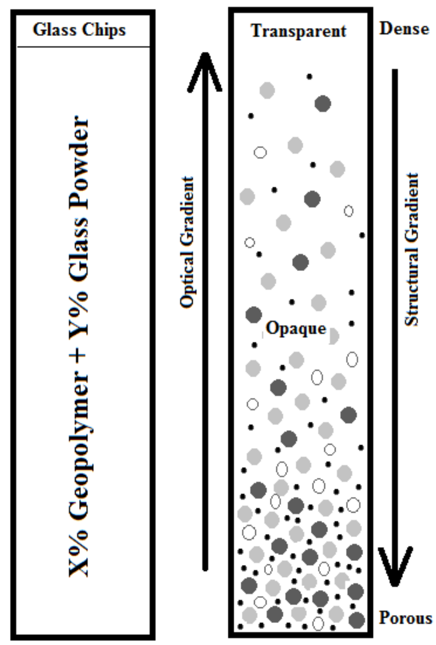
<table>
<tr><th>Layer #</th><th>GP (X%)</th><th>Glass Powder (Y%)</th><th>Glass Chips</th><th>Picture of final product</th><th>Schematic picture of functionally graded material</th></tr>
<tr><td>1</td><td>80</td><td>20</td><td rowspan="4">0</td><td rowspan="5"></td><td rowspan="5">
</td></tr>
<tr><td>2</td><td>20</td><td>80</td></tr>
<tr><td>3</td><td>10</td><td>90</td></tr>
<tr><td>4</td><td>5</td><td>95</td></tr>
<tr><td>5</td><td>-</td><td>-</td><td>100</td></tr>
</table>

Table 7- 21-layer column of functionally graded material made of low-iron glass while glass chips was exposed to the air

Layer #	GP (X%)	Glass Powder (Y%)	Glass Chips	Picture of final product	Schematic picture of functionally graded material
1	0	0	100		
2	0	100	0		
3	5	95			
4	10	90			
5	15	85			
6	20	80			
7	25	75			
8	30	70			
9	35	65			
10	40	60			
11	45	55			
12	50	50			
13	55	45			
14	60	40			
15	65	35			
16	70	30			
17	75	25			
18	80	20			
19	85	15			
20	90	10			
21	95	5			

SUMMARY

This work studies the influential parameters on the qualities of FGMs made of binary blends of transparent material (glass) and ceramic material (GP) to form a strong interface. The small samples were designed and developed for the preliminary works to finalize the sintering process, GP and glass powder compositions, exposing condition, and layering thickness. It was observed that:

[1] The sintering process should be engineered depending on the size and composition of powders used.

[2] GP and glass powder composition can influence their CTE, as such, the choice of either GP or glass powder should be engineered to minimize the difference between CTEs of initial powders (GP and glass powder). To prevent any cracking in the ceramic part, it might be good to add small proportion of glass powder (5% or more) and avoid using 100% GP in a layer. In this work, combination of GP1 (check Table 2) and low-iron glass resulted in the most flawless products.

[3] When the GP was exposed to the air during the firing process, it shrank and the noticeable volume change was seen between the top and bottom layers, while for low-iron glass powder exposed to the air, there wasn't any considerable volume change at the top layer.

[4] Gradual change of material composition would be better to be distributed in a smaller increment along the sample with a slight change between the compositions of successive layers.

[5] By scaling up the specimen size, new problems would be faced and the entire

process may need to be revisited and engineered.

CONCLUSIONS

Often the architect's creative ideas are compromised because the status quo renders them unattainable. FGMs present many possibilities allowing clearer translation of creative ideas to built-form. The use of Functionally Graded Materials in lieu of the unnecessary layers and joints will undoubtedly bring attention to new technologies, and engineering of the latent behavior in familiar materials such as concrete and glass.
We have been able to form a strong interface between glass and geopolymer-based advanced ceramics through casting and sintering processes at the laboratory scale, achieving a seamless union between these two distinct materials, which are sintered and joined without the presence of a tertiary element. The Scanning Electron Microscopy of Microstructural detail of the union between the GP and dense soda-lime glass at the interface shows that there are no gaps or cracks between them. After achieveing the perceptible and sharp but seamless transition we pursued the goal of creating a Functionally Graded Composite Material containg a varying degree of GP and soda-lime glass that can have more structural capacity where there is more concentration of GP concrete; more environmental and thermal capacities due to its closed porosity with varying thickness or manipulation of its internal porosity as needed; and optical transparency as it approaches 100% glass to GP ratios. To achieve this seamless transition (sharp or graded), post processing at high temperatures is a necessity because only then the interface between glass and GP becomes impermeable, airtight, and watertight. We are exploring low temperature processes and other types of post-processing in our future steps.
It is exciting to think about the crucial role that architecture can play in bringing attention, focus, clarity, and purpose to advanced materials and technologies. In fact, not only the orchestration of new materials and techniques of construction, but the interrelationship between various disciplines have been manifested through intelligent architectural masterpieces throughout history.

ADVANTAGES/ APPLICATIONS

We recognize that unless the structure is made of prefabricated components, post processing of larger monocoque structures at this point is limited to the size of the kiln. Although we present experiments using casting technologies, we believe that the true benefits of FGMs can be explored through additive manufacturing or hybrid technologies that combine the two. We have already made considerable advancements of additive manufacturing of GP-based concrete and are exploring field specific techniques of post processing in the near future.
Additive manufacturing of GP- based functionally graded composite materials (FGVMs) enable precise and efficient use of materials and labor, better safety measures in construction industry, less carbon footprint and more sustainable practices and materials. FGCMs can be designed, adjusted, and distributed voxel by voxel as the robotic arms or other AM manufacturing deposition and/or sintering techniques can be guided by versatile BIM interfaces. As such, construction efficiency can be tremendously optimized.

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Additive Manufacturing of Functionally Graded Building Parts: Towards Seamless Architecture

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ABSTRACT

Architects and engineers are under increasing pressure to improve the efficiency and effectiveness of the building sector, reducing environmental impacts, material use and costs. Resource efficiency, based on a circular economy strategy, considers an efficient use of energy, natural resources, and materials. The use of natural insulation materials is a good solution to reduce the depletion of earth's natural resources, making buildings healthier and more durable and sustainable. This paper describes the use of additive manufacturing (AM) process to produce functionally graded building parts using cement-based mixtures containing different amounts of cork granules. Cork is a natural and sustainable raw material, completely biodegradable, renewable, and recyclable. Furthermore, cork mechanical and thermal properties, and its environmental footprint assist designers, architects, and engineers in achieving green building requirements. In addition, the integration of Additive Manufacturing (AM) in construction will allow for a greater flexibility in design and the customization of building parts for optimized performance. A multi-pump robot system was developed to produce functionally graded building parts.

INTRODUCTION

Construction practices need to be improved, reducing their adverse effects on the planet (Cole, 1999). Resource efficiency aims at an efficient use of energy, natural resources, and materials. The construction sector is responsible for one third of Earth's resource consumption, generating large amounts of solid waste (European Commission, 2014). Buildings also are responsible for almost a third of energy consumption and are a significant source of CO_2 emissions (OECD/IEA, 2011; Ürge-Vorsatz et al., 2012). Enhancing the thermal properties of building materials is a key to improve building energy efficiency (Cherki et al., 2014). Traditional insulation technologies composed by several layers of insulation materials increase the thickness of the building envelope, raising costs and creating restrictions for architects and engineers (Jelle, 2011).

Building seamless walls with optimal thermo-mechanical properties can help to reduce waste generation, emissions and global resource consumption. Besides, thin/lightweight walls avoid overloading the building structure, reducing cement consumption (Binici et al., 2016; Craveiro et al., 2016; OECD, 2015). Incorporating natural insulation materials, such as alternative aggregates processed from waste materials or natural and renewable materials will create buildings that are healthier and more durable and sustainable (Scrivener and Kirkpatrick, 2008). Cork is a natural and sustainable raw material, harvested from Oak trees (Quercus suber L) (Gil, 1997). Cork is completely biodegradable, renewable, and recyclable. Properties such as low density, impermeability, low conductivity, chemical stability and durability, fire retardant, highly wear-resistant and near zero Poisson's ratio make cork a very suitable as a construction material. Only about ¼ of the harvested cork is used to produce high quality punched bottle stoppers, the remaining is considered waste and used for diverse industrial applications, after a granulation process. In the construction sector, this rejected cork is mainly used as a lightweight aggregate for concrete and mortars (density ≈ 150–160 kg/m^3), or for thermal (thermal conductivity ≈ 0.049–0.05 W/m×K) and acoustic insulation (Andrade, 2016; Brás et al., 2013; Costa et al., 2010; Karade et al., 2006).

Most structural materials, such as concrete, are manufactured with uniform properties and designed to resist to maximum stress, which may only occur in a small area, so quite often the use of resources is higher than really needed (Dias et al., 2010; Gupta, 2014). On the other hand, AM technologies, which build parts by adding layers of material upon one another, have been investigated for the construction sector (Craveiro et al., 2017b), but mainly to fabricate building parts with homogeneous material properties (Oxman, 2011; Sing et al., 2017). Inspired by nature, functionally graded materials (FGM) (Craveiro et al., 2013; Ray et al., 2005), are characterized by a spatial variation in material properties regarding composition and microstructural gradient, which can be customized to specific thermo-mechanical loading conditions (Craveiro et al., 2017a; Miyamoto et al., 1999). Using heterogeneous composite materials with a variable material distribution for distinct functional requirements, like natural structures, will enable to model, simulate, and fabricate construction elements for specific loading conditions.

In the present work, to produce cement-based building parts with spatially varying compositions, mixtures containing different amounts of cork granules are investigated, and an AM system, composed by a multi-pump robot system is presented.

METHODS AND MATERIALS

Material and Mixture Design

In this study, various cement based concrete mixtures with different aggregate ratios were designed. Pennsylvania river sand and cork were used as aggregates. The volume of aggregates was kept constant for all mixtures. Cork granules replaced different volume fractions of sand. The maximum size of aggregates had to be controlled according the nozzle and pump dimensions, which are detailed in the next section.

The sand was firstly dried at 110°C for 24 hours, and then sifted through sieve nº16 (1.19

mm). To guarantee a particle size distribution of cork granules close to the sand, a mixture of three commercial sizes was prepared, respectively with 30% of cork granules size “14/30”, 35% of size “20/40” and 35% of size “40/80” (Figure 2). The Faury grading curve presented in Figure 1 presents the particle size distribution of the aggregates.

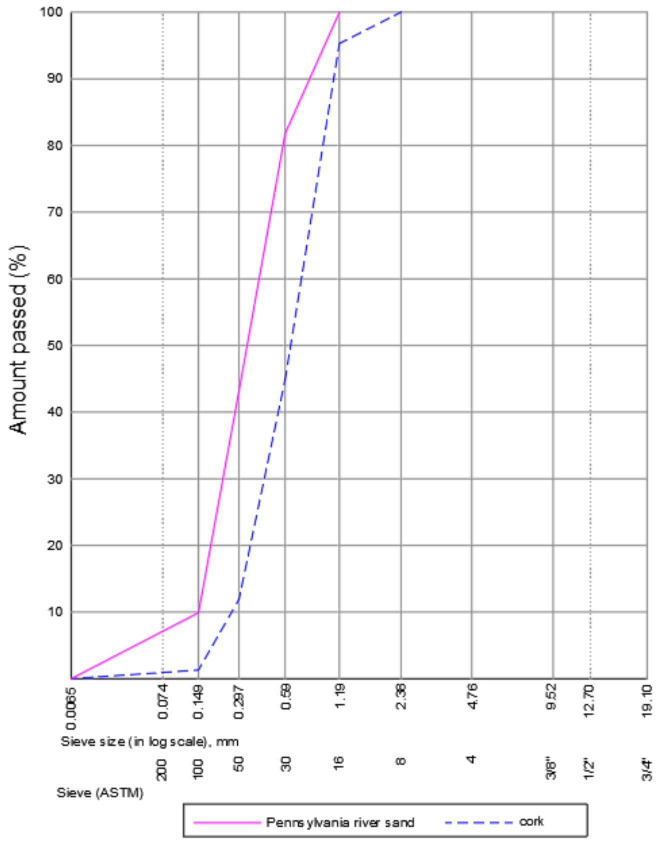

Figure 1. Faury grading curve, cork and sand particle size distribution.

Figure 2. Cork granules, different sizes used in the composition.

An ordinary Portland cement concrete (C0) was developed. The proportioning of the different ingredients was selected taking pumpability and the slump value into account. The material needed to be strong enough to hold its weight and the weight of upper layers after printing, but workable enough to be printed with our small pumps.

Based on this base mixture, four other concrete mixes were designed by replacing part of the sand with cork granules, namely:

i) C25 at where 25% of the sand volume was replaced by cork;

ii) C50 at where 50% of the sand volume was replaced by cork;

iii) C75 at where 75% of the sand volume was replaced by cork;

iv) C100 at where 100% of the aggregate is cork.

A dry admixture named Gibco powder was used to replace lime and to serve as plasticizer, increasing the workability, as air entraining giving better resistance to freeze and thaw and as a water reducer to increase compressive and bond strength. The superplasticizer used in this study was Sika Viscocrete 6100.

The mixing procedure is as follows:

1- Dissolve Gibco powder in water and add superplasticizer to the solution.

2- Pour the cement and mix at slow speed (140 ± 5 rev/min) for 30 seconds.

3- Add sand (or sand + cork) gradually to the paste within 30 s and blend them at slow speed (140 ± 5 rev/min).

4- Stop the mixer and let the mixture stand for 90 s.

5- Mix the mixture for 60 s at medium speed (285 ± 5 rev/min).

6- Turn off the mixer and spoon down the material into the pump.

After several experiments with different mixture compositions, the optimal mixtures were as shown in Table 1.

Table 1. Composition of concrete mixtures C0, C25, C50, C75 and C100.

Materials (g)	C0	C25	C50	C75	C100
	wt (%)	wt (%)	wt (%)	wt (%)	wt (%)
Water	12.68	14.55	17.06	20.63	26.07
Cement	31.71	36.38	42.66	51.57	65.18
Sand	55.48	47.74	37.32	22.56	0.00
Cork	0.00	1.18	2.78	5.03	8.48
Superplasticizer-Sika	0.11	0.13	0.15	0.19	0.23
Gibco powder	0.02	0.02	0.02	0.03	0.04
total mass	100%	100%	100%	100%	100%

After mixing the materials, each mixture was poured into 2 inches cubes to determine the mechanical properties. The specimens were placed in a moisture room during the curing process of 28 days (Figure 3).

Figure 3. Preparation of the cube specimens: a) sand sifting, b) materials and mixer, c) prepared specimens, d) moisture room.

Mechanical System Design

To produce functionally graded building parts, an extrusion AM system was developed. The hardware consisted of two pumps to extrude the materials, and an industrial 6-axis robotic arm, ABB IRB 2400, which provided various ranges of movement in different axes. An Arduino-based interface, connected to the robot controller, synchronizes the movements of the robot with the pumping speed. Each pump reservoir holds a single mixture, one containing fine-aggregate concrete with a high concentration of cork and the other a sand-based concrete. By varying the pumps' speed ratio, it is possible the continuous production of material with different gradient. A 15 mm diameter nozzle was used for extruding the material.
All the digital information required to control the pumps is generated in a grasshopper plugin, called HAL, combining the tool path information with the designed material composition, and then compiled in a .RAPID file, an ABB high-level programming language. Figure 4 shows a schematic diagram of the developed system.

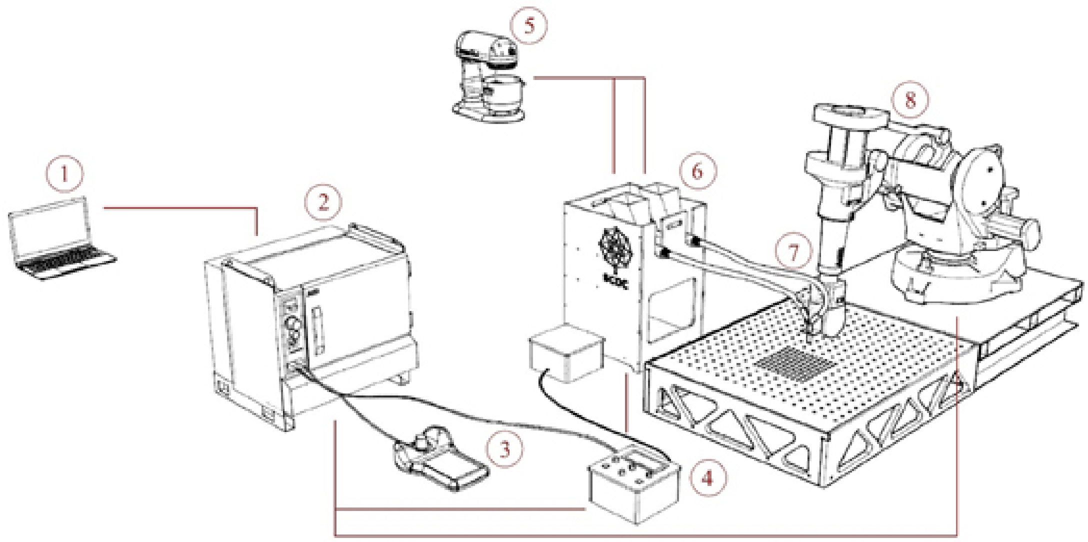

Figure 4. Diagram of the AM of concrete system: 1) Computer for designing the material and the toolpath and generating the robot code, 2) Robot controller, 3) Robot tech pendant for hand control, 4) Pumps tech pendant for hand control (Arduino based interface), 5) Mixer for materials preparation, 6) Concrete pumps, 7) Dynamic mixer/ extruder nozzle, 8) Robot.

Tool Path and material variation

In this study, the toolpaths were computed and generated in Rhinoceros and Grasshopper. The 3D-printing toolpath design, the printing speed, and the nozzle size, are important factors to obtain a successful result, affecting the fresh properties of the different mixtures (Hojati et al., 2018).
A freeform building part was designed, to be produced using a filament with a diameter of 15 mm (internal nozzle size), as shown in Figure 5.

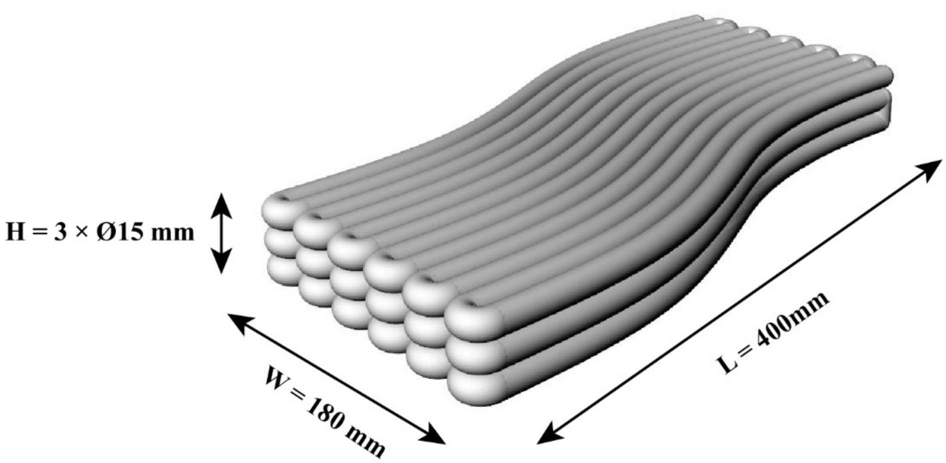

Figure 5. Digital model of the printed building part, showing the dimensions and the layering of filament (3 layers).

It was decided to materialize the building part with a spatially varying composition. The production starts with the ordinary Portland cement concrete (C0) and gradually changes to the mixture with 25% of cork (C25), as shown in Figure 6.

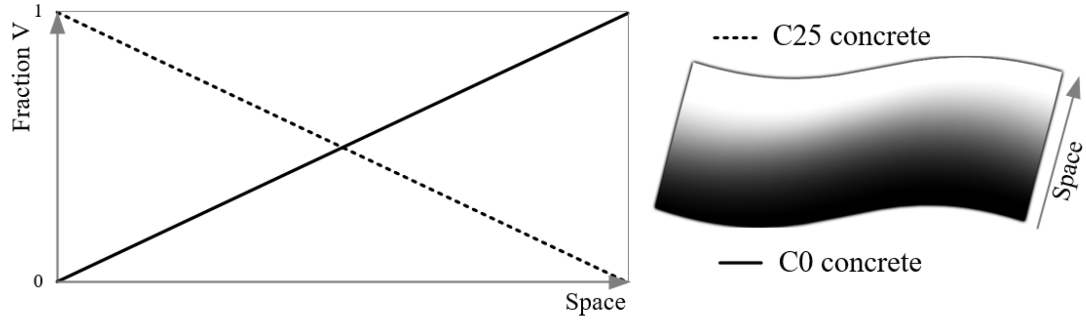

Figure 6. Volume fraction variation of each single mixture (left), Top view of the printed building part showing the gradient direction (right).

RESULTS AND DISSCUTION

Mechanical tests of the cube specimens

The compressive strength of the specimens was determined at 28 days in accordance with the ASTM Standard C109. The samples were tested on a Boart Longyear model CM-625 testing machine (Figure 7).

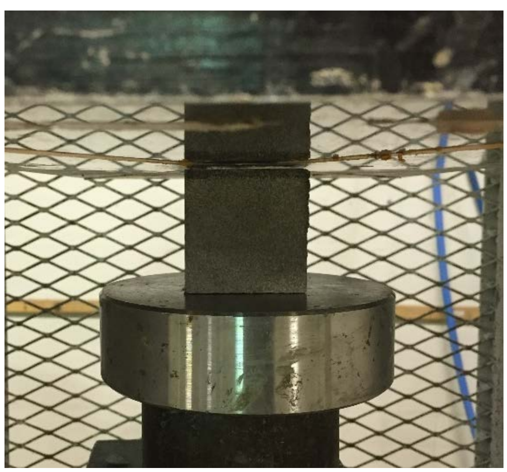

Figure 7. Compression test of a cube specimen.

Dry density properties are presented in Figure 8 and results of compressive strength are shown in Figure 9.

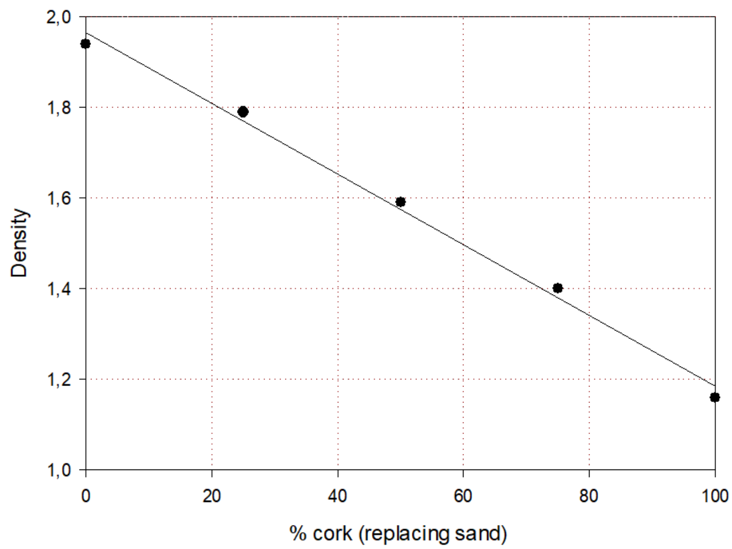

Figure 8. Dry density.

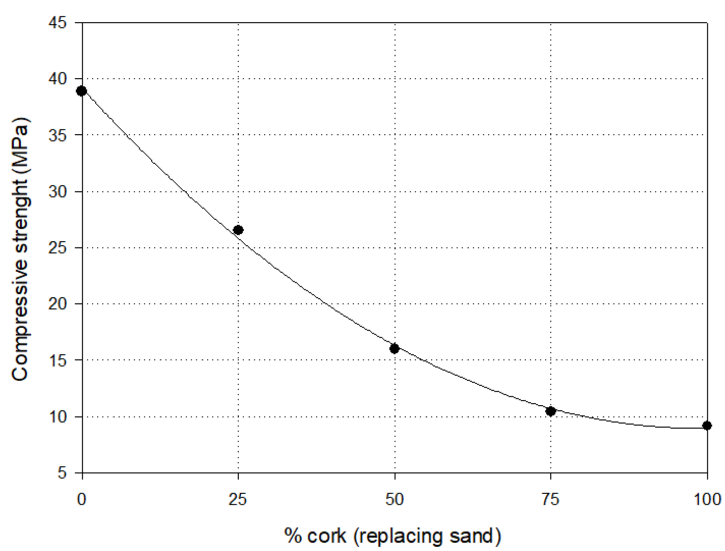

Figure 9. Compression results.

Density and compression results can be compiled into a material database or translated to material equations, serving the computational tool. Accurate material properties support the design of structures with an optimized material distribution.

Functionally graded building part produced by AM

A functionally graded building part, with a seamless transition of its properties, was produced through the developed AM system. A generative tool, described by Craveiro et al. (2017b), was improved and used to design the material according the gradient proposed in Figure 6. This computational tool is also used to control the movements of the robot and the speed of each pump. Each pump reservoir holds a single mixture, one containing the mixture C0 (sand-based concrete) and the other containing the mixture C25 (25% of cork). By varying the pumps' speed ratio, it is possible the continuous production of a functionally graded material. In real time, the Arduino-based interface, synchronizes the movements of the robot with the pumping speed.

a) b)

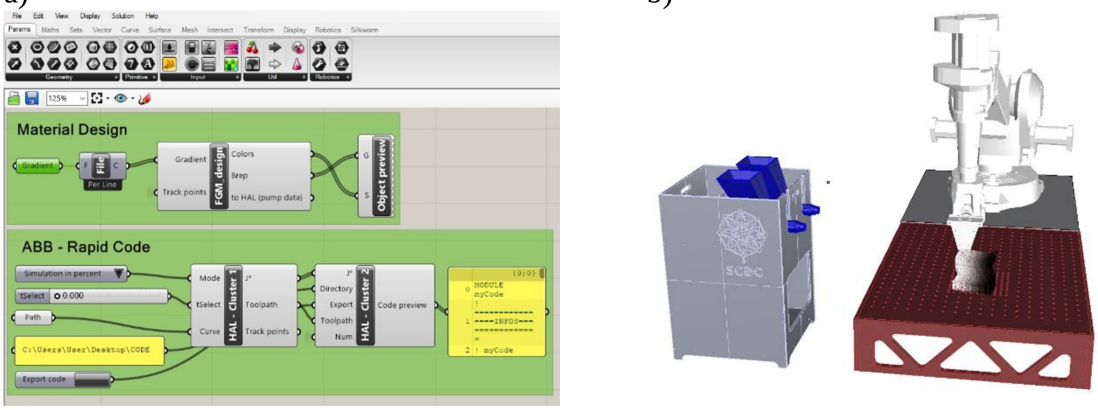

Figure 10. Generative tool: a) grasshopper code, b) visual output in Rhinoceros showing the varied material composition in graded color.

After filling each of the pump reservoirs, the mixture is then extruded through a single nozzle which blends the two materials flowing from the pumps (Figure 11). In the tool path, the thickness of each filament was designed to be 15 mm, and the movement speed of the robot was 25 mm/s. These values were adjusted after several trials, according to the material flowability and the pump speed limit. A three layer functionally graded component was successfully produced, as shown in Figure 12.

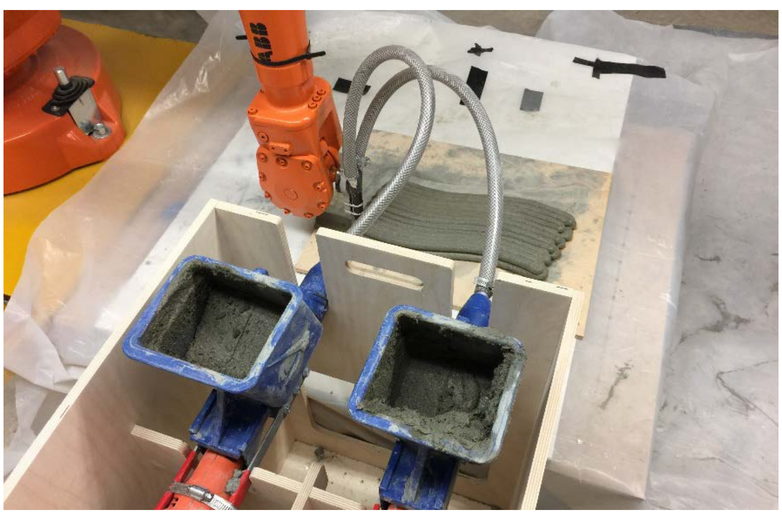

Figure 11. AM System extruding a functionally graded component.

Figure 12. Cement-based functionally graded component produced.

CONCLUSIONS

There is a need to improve construction practices, including enhancing the envelope of building, thereby contributing for energy and material efficiency. The use of alternative natural aggregates, rejected from of other industries, can also contribute for a more sustainable building sector. The study of cement-based materials with different concentrations of lightweight aggregates, together with the development of a generative computational tool and an additive manufacturing system, permits to successfully produce functionally graded building parts. This FGM concept allows the creation of resource-efficient graded building parts tailored to specific conditions, and simplifies construction by enabling seamless transition between parts with different material properties. Future work will focus on the influence of cork percentage on thermal properties and the improvement of the extrusion head.

ACKNOWLEDGEMENTS

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Implications of Indoor Environmental Quality Criteria on Building Occupants

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ABSTRACT

The implications of clean and serene environment on the life of individuals cannot be overemphasized. In view of this, this research examines the effects of various criteria of indoor environmental quality (IEQ) on the comfort, health, safety and wellbeing of building occupants. Various environmental problems and their effects were reviewed from existing literature materials. The factors were further adopted in the development of closed-ended questions aimed at determining the implications of IEQ on building occupants, and the questions ranges from habits of the building occupant to various activities carried out by them and their frequencies. Survey method was adopted in the distribution of questionnaires comprising the questions on residents of selected areas and their responses were analyzed using simple descriptive statistical tools. The study revealed that a larger percentage of building occupants in the study area experience fatigue and headache which are attributed to issues of IEQ. It was also discovered that presence of smokers as occupants of buildings has severe effect on the comfort and well-being of occupants depending the number of smokers, number of cigarettes and place or areas dedicated to smoking. Cooking method and level of cleanliness of the occupants were also found to be major IEQ factors affecting quality of life of building occupants. It is therefore necessary for building occupants to pay attention to aforementioned factors and work together to ensure that activities that can jeopardize their comfort are eradicated or reduced to the barest minimum. More so, building developers, contractors and other stakeholders should also take into consideration such factors as smoking area (outside the building) and cooking methods among others in the planning, design, execution and usage of buildings.

Keywords: Comfort, Indoor Environmental Quality; Smart Structure; Health and Safety.

INTRODUCTION

A more practical definition of indoor environmental quality (IEQ) that suitably defines the objectives required of this study is given by National Institute of Occupational Safety and

Health (NIOSH, 2015), IEQ was defined as being a condition related to comfort, quality and experiences within any building that directly have a bearing on the occupants in ways such as impacting their physical health. The creation of comfortable living conditions has long been a goal of the human race and the constructed dwelling wherein they reside, should it cause illness or discomfort, would suggest that there has been a technical flaw in the design of the dwelling or the physical construction thereof in the sense of materials used and this discomfort that can be posed by dwellings has an immediate health effect on the occupants and needs to be tended to (Galatioto et al., 2016).

The problems that IEQ poses on the inhabitants of buildings are summarized and tabulated in table 1 according to Malmqvist (2008). Samet et al (1998) and Mitchell et al. (2007) maintain that previous studies focused primarily on indoor air contaminants but the authors also maintain acknowledge that the research processes and developments have become more effective in recent years and thus research has tended to include another paradigm to the indoor environmental quality phenomenon namely, creating a relationship between buildings and their occupants and IEQ. This study is construed due to continued focus on the implications of indoor environmental quality on building occupants as opposed to studies on the satisfaction that occupants hold with the indoor environmental quality. More so, satisfaction studies are growing and it is desirable for implication-related studies to grow as these are more connected to the human element i.e. health of the occupants.

Table 1: IEQ problems and associated effects

Problem	Severity
Lung cancer from radon exposure	High mortality rate
Legionnaire disease	Approximately a 10% mortality rate
Allergy	Can be fatal
Sick building syndrome symptoms	Fatigue, headache, cough, skin irritation, running nose, eye irritation and sore throats
Sleeping disturbances from traffic noise	Fatigue, stress, hypertension and reduced working ability
Traffic noise annoyance	Annoyance and perceived discomfort
Neighbour noise annoyance	Annoyance and perceived discomfort
Installation noise annoyance	Perceived discomfort
Concentration problems	Fatigue, reduced working ability and reduced speech comprehension
Annoyance as a result of a cold internal environment	Reduced working ability
Annoyance as a result of a hot internal environment	Reduced working ability
Heat wave deaths	Mortal
Annoyance due to insufficient daylight	Fatigue and sleep disturbances
Annoyance due to insufficient direct daylight entering the house	Annoyance and perceived discomfort
Annoyance from sun glare	Reduced working ability
Electromagnetic field sensitivity	General symptoms
Children’s leukemia	Severe chronic illness, fatal.

Bad tap water illnesses	Acute diseases

Source: Malmqvist (2008)

RESEARCH METHODOLOGY

Descriptive survey was adopted in this study because it provides accurate portrayals or accounts of characteristics being investigated such as behavior patterns and knowledge about a particular situation hampering individuals or a group. The design was adopted to meet the research objectives of the study which is to determine the implications of indoor environmental quality on the building occupant health and physical well-being.

The information was collected through self-administered questionnaires that were personally handed out by the researcher. The study was conducted in Dundee, particularly in the Eighteen and Twenty low-income housing areas which fall under the Endumeni Region, UMzinyathi District in the province of Kwa-Zulu Natal, South Africa. The areas cater for the people living in the Endumeni Region who meet the criteria for having a Reconstruction and Development Plan (RDP) house. The population consists of occupants residing in the areas that are above the age of eighteen, all of which had to be permanent residents of the buildings.

The data in this research was collected through the usage of a questionnaire to examine the occupants' experiences within their homes and their satisfaction with the indoor environmental quality therein. The administered questionnaires were in lay English and isiZulu in order to enable every participant to understand and respond adequately. The respondents were assured that their answered would not be linked to them at any stage, thus ensuring anonymity to the respondents. Clear instructions were given to the respondents and the researcher completed the questionnaires for people that could not read. All the subjects completed the questionnaires in the presence of the researcher, and this was done to prevent subjects from giving questionnaires to other people to complete on their behalf.

Convenience sampling approach was used, as the research respondents were surveyed based on their availability and ease of access by the researcher considering the vast area of the study area. The building occupants residing in the selected area were expected to meet the following criteria in order to be considered:

- Minimum age of 18 years
- Mentally sound
- Willing to participate in the study (No one was forced or otherwise bribed)
- No bias for sex/gender
- They needed to have passed grade 9 at least in terms of educational achievements
- Living in the current house for a minimum of 3 months.; and
- If any other people lived in the house with any of the respondents, they too had to meet the criteria in order to participate.

At the end of the data collection process, 54 questionnaires were retrieved from the 60 distributed. Data was analyzed using descriptive statistics, mean item scores (MIS) and standard deviation were adopted to rank and determine the implications of various IEQ criteria on the quality of life of building occupants.

FINDINGS AND DISCUSSION

This section comprised of 15 questions aimed at determining the implications that indoor environmental quality has on building occupants and the questions range from habits of the building occupant to the activities the respondents carry out and how often they are carried out.

From the study conducted, the main function of asking the allergy related questions was to determine whether any of the respondents were experiencing any allergic reactions or allergies that could be attributed to the indoor environment. The study showed that the respondents were experiencing allergies namely asthma and food allergy, of which asthma is considered an allergic condition that can be attributed to the indoor environment. The respondents were asked if they experienced fatigue in their homes. Of the 54 respondents, 49 (90.7%) replied yes and 5 (9.3%) replied no. Literature has documented reasons that occupants could experience fatigue and these include the experience of SBS symptoms in the workplace, concentration problems which could be as a result of noise in and around the building, sleep disturbances and perceived discomfort due to glare of light or the absence of sunlight (Malmqvist, 2008). Excessive heat in the area of Dundee during the cold season could be responsible for making the building temperature rise well above the comfort temperature thus, causing excessive room temperature which in turn causes fatigue. Jansz (2011) noted that the absence of acoustic comfort is a main cause of fatigue and if these elements are all combined it can result in long-term fatigue being experienced i.e. excessive heat temperatures and noise levels beyond the tolerance threshold. Low income areas generally have large, densely packed housing close to one another and close to the roadways, this could be the underlying factor as to why noise levels are not only significant to the building occupants but also that noise levels are always a matter of concern with regard to satisfaction with buildings as traffic noise during the night creates sleep disturbances. The high “yes” rate explains that many of the respondents are hampered by the facts mentioned above.

The respondents were then asked if they ever experience any inexplicable headaches in their homes and whether they attribute them to indoor environmental quality of the building they reside in. There were a total of 45 respondents who claimed experiencing fatigue in their homes and 36 respondents of the 45 said they attribute the fatigue experienced to factors related to indoor environmental quality. The experience of inexplicable headaches while in the home could be caused by experience of glaring light which creates pain and discomfort in the form of migraines and this takes place in a person’s subconscious and the effects do not take effect immediately. The inexplicable headaches could be explained by literature as being as a result of being in contact with fluorescent lighting in the home or the work place (at home fluorescent lighting can be found in the form of table lamps, bedroom lamps and any other forms of artificial lighting such as incandescent lamps in homes. One the most frequent experiences in buildings that create discomfort are headaches together with excessive fatigue which may be frequently experienced or on several days and affect the frontal lobe of the brain in similar fashion to a migraine and are attributed mainly to the presence of artificial lighting in building and fluorescent lights and can be alleviated by moving from the artificially lit room and or the wearing of sunglasses in order to prevent the sensation of these headaches which in effect do lead to fatigue (European Concerted Action, 1989; Jansz, 2011). In effect, this phenomenon is mainly as a result of the occupant altering the environment through the introduction of artificial lighting to the building and depending on the quantity, that will be the degree of discomfort experienced in due proportion.

The respondents were then asked if they ever experience itching and burning of the eyes in their homes and whether they attribute them to indoor environmental quality of the building they reside in. There were a total of 23 respondents who claimed experiencing fatigue in their homes and 17 respondents of the 23 attributes it to factors related to indoor environmental quality. Joshi (2008) states that sick building syndrome is a phenomenon that arises and causes a large amount of discomfort in terms of health of well-being of building occupants provided that they spend sufficient time within it, these discomforts include acute health effects and in some cases, allergies and allergic reactions, physical discomfort such as fatigue and burning of the eyes and also sickness caused by building features i.e. the amount of sunlight entering the building. The discomfort of the eyes is experienced when speaking about ocular manifestations as building occupants experience an array of eye-burning sensations as a result of the breaking up tear film in the eyes but, fortunately these manifestations are prevalent on people who wear contact lenses rather than those who do not (European Concerted Action, 1989; Jansz, 2011). This sensation is not commonly experienced in residential buildings and those who responded with a yes are most likely people working and are coming into contact with discomfort in the work place.

From the analysis, 41 (75.9%) of the respondents smokes or have smokers in their house while the reaming 13 (24.1%) do not smoke nor have a smoker as occupant. Of the 41 respondents with a smoker as occupants, 22 (53.7%) of the respondents said that the smoker(s) smoke outside, 6 (14.6%) in the bathroom and 13 (31.7%) in one of the rooms in the house. Of the 6 reported smokers reported to be smoking in the bathroom, 1 smoked between three and five cigarettes and 5 smokes between five and ten cigarettes. Of the 13 reported smokers reported to be smoking in the various rooms in the house 4 smoked less than three cigarettes per day, 3 smoked between three and five, between five and ten and more than ten cigarettes per day. On the amount of cigarettes the smoker(s) smoke per day, 8 (19.5%) of the respondents reported that smokers smoking less than 3 cigarettes a day, 6 (14.6%) reported between three and five, 17 (41.5%) reported between five and ten and 10 (24.4%) reported more than ten cigarettes are smoked.

Table 2 depicts a relationship between the location of the smoking activity and the amount of cigarettes smoked. The main objective of asking the smoker-related questions was to determine the implications that smoking has if any, on the indoor environment. The function was also to determine whether the indoor environment was influenced in a long or short term and to determine whether literature agrees with the findings. The implications of environmental tobacco smoke are documented in literature as being a result of particles and fibers being in and around the building. These factors are always increased if there is a dirt road near the building as the dust particles from the outside will now be transported from the floor and outdoor air into the building creating chest tightness in time and wheezing as the dust particles stick to the chest (European Concerted Action, 1989; Jansz, 2011).

Tobacco smoking affects not only the smoker, but, the people he or she smokes around and depending on the location of the smoking activity. The impacts of the smoking activity are stronger if the smoking occurs indoors as this carcinogenic gas sticks onto the furniture, walls and indoor air and depending on how many cigarettes are smoked in the location, the longer the gas stays in the indoor environment thus harming the residents. Environmental tobacco smoke is not essentially an indoor environmental quality issue related to the building itself, but rather as a result of occupants contaminating the environment with their smoking. This is the strongest contributor of indoor pollution and poses deadly consequences such as the well-known fact that smoking causes cancer and lung, heart, gum and other diseases and the passive smoker is more susceptible to the effects of sick building syndrome than the equivalent ex or non-smoker when exposed to environmental tobacco smoke (European Concerted Action, 1989; Jansz, 2011). The irritation of the mucous membrane thus leading gradually to lung cancer due to secondary smoke being inhaled and the concoction of chemicals destroy what is left of the body. “Formaldehyde is a colorless, flammable gas with a pungent, suffering odor which is released into the air from forest fires, car exhaust fumes and tobacco smoke according to the Healthy Building Network (2008).”

Table 2: Relationship between location of smoker(s) and amount of cigarettes smoked

Smoking area	Number of cigarettes	No of people
Outside	Less than three cigarettes	4
	Between three and five cigarettes	2
	Between five and ten cigarettes	9
	More than ten cigarettes	7
Bathroom	Between three and five cigarettes	1
	Between five and ten cigarettes	5
Rooms	Less than three cigarettes	4
	Between three and five cigarettes	3
	Between five and ten cigarettes	3
	More than ten cigarettes	3

The cooking portion of the questionnaire aimed to determine the implications that the process has on the indoor environment and to also determine the implications of those on the occupants of the house. Depending on the amount of cooking that occurs in a building and the means of cooking, certain implications prevail on the occupants of a building as a result of the fumes released by the cooking itself and the stove used to cook.

Findings revealed that 28 (51.9%) of the respondents use an electric stove while 26 (48.1%) use a gas stove. Using these means, 15 (27.8%) of the respondents cooks twice or thrice a week, 35 (64.8%) cooks daily and 4 (7.4%) cooks more than once a day. Literature shows that gaseous substances are released during the cooking process such as carbon monoxide (European Concerted Action, 1989; Jansz, 2011). This carbon monoxide that is inherently a result of combustion could prevail as a result of cooking, smoking and car exhaust fumes. Wiesel (2005) states that primary indoor pollutants are as a result of cooking whereas Dubowski et al. and Mitchell et al. maintain that surfaces reactions are a significant contributor to the quality of the indoor environment and arise as a result of the volume to surface area indoors being significantly higher than the surface to volume area present outdoors and this leads to the prevalence of illness within the building given that more reactions can take place indoors given the confined space in a building and higher contact ratio, leaving the building occupants to experience the aftermath of these reactions which are as a result of cooking, cleaning bathing and other household activities (Dubowski et al. 2004; Mitchell et al., 2007). The gas stove causes carbon monoxide to be released into the atmosphere which causes chest tightness and wheezing although these last a short while. The amount of cooking done using a gas stove increases the likelihood of having these effects hampering the occupants and a gas stove used indoors releases this gaseous substance and if the interior has been painted with synthetic paint, an indoor chemical reaction will occur resulting in the paint releasing its chemicals into the atmosphere along with those released from the cooking process resulting in further discomfort if a gas stove has been used

Table 3 displays the frequency with which the respondents clean their homes. 3 (5.6%) of the respondents clean their homes more than once a day, 20 (37.0%) cook daily, 28 (51.9%) cook once a week and 3 (5.6%) cook between two and four times a week. Cleaning prevents the development of dust particles indoors as the indoor environment will be hygienic and prevents any and all dirt related implications to prevail. A clean environment removes mites that could have been brought in by the occupants from either pets they were in contact with or children bring them in via contact with mattresses at school. The more frequently a person cleans the building, the more hygienic and free from dust or odor related indoor environmental quality implications.

Table 3: Frequency of house cleaning

Cleaning	Frequency	Percentage
Several times a day	3	5.6
Daily	20	37.0
Once a week	28	51.9
Between two and four times a week	3	5.6
Total	54	100.0

The respondents were asked whether they make use of vacuum cleaners, humidifiers and dehumidifiers and table 4 depicts the results obtained from the survey. Vacuum cleaners were the most used by the respondents and no indoor environmental quality health and well-being effects are attributed to the use of this device as it in fact removes particulate matter that causes illness such as dust and dirt which can prevail in environments that are carpeted so the employment of this cleaning device is necessary. Humidifiers were the second most used devices according to the respondents surveyed with 10 respondents making use of this device. Indoor environmental quality health and well-being effects can prevail from the use of this device as noted in literature, though the development of an illness known as humidifier fever.

Humidifier fever is a “fever” that prevails in the victim’s system for a full day but has no lasting effects after the evening of the contraction, these effects start early in the day and progress in aggression throughout the duration of the day and have no carry-over effects to the new day, but, if the person remains in the building the person will experience symptoms similar to those of the flu, fatigue or lethargy, sharp and painful headaches, nasal congestion and fever symptoms along with rarer ones such as myalgia and arthralgia (Right Diagnosis, 2014; National Heart, Lung and Blood Institute, 2016). In good fortune, as noted above these effects are not long lasting but, continued exposure will result in continued effects being experienced and the flu that is mild will get stronger as the use of the humidifier continues and this could be problematic.

Table 4: Devices used by occupants for indoor cleaning

Type of device	Frequency of usage	Percentage
Vacuum cleaner	27	71.1
Humidifier	10	26.3
Dehumidifier	1	2.6
Total	38	100.0

CONCLUSION

The experience of fatigue in the home was explained by literature which has documented reasons that occupants could experience fatigue and these include the experience of SBS symptoms in the workplace, concentration problems which could be as a result of noise in and around the building, sleep disturbances and perceived discomfort due to glare of light or the absence of sunlight. These above are the implications of the experience of fatigue in the workplace.

In conclusion, the excessive heat in the study area during the cold season could be responsible for making the building temperature rise well above the comfort temperature thus, causing excessive room temperature which in turn causes fatigue. Glaring light, which was not one of the satisfactory elements of indoor environmental quality according to the respondents surveyed is a known cause of this phenomena and is an indication that a portion of the buildings are not placed in a manner that provides an angle that reduces or negates the effects pf the glare from the sun's rays, but, it can also be said that given the lower satisfaction rate, a minority of the respondents suffered from this indoor environmental quality health/well-being issue.

Given that the itching and burning of the eyes is a health and well-being issue related to people who make use of contact lenses, this was a less prevalent issue. The health and well-being issues related to cooking done in a building was mainly due to the use of a gas stove, and those who made use of a gas stove depending on the frequency with which they cook, were affected by the health issues, and it can be said that electric stoves do not have any health and well-being issues related to the combustion occurring during the process.

With regard to cleaning, results show that the more the occupants clean the building, the less likely they are to experience any implications posed by indoor environmental quality elements in a building and in conclusion, that cleaning is good for the building as it alleviates elements such as dust and dirt and foul odors in the building. The humidifier poses health and well-being implications on building occupants such as humidifier fever and flu although the effects are not long lasting. With respect to the above, the implications posed to the occupants by the above are as mentioned and it can therefore be concluded that the third objective was achieved.

IMPLICATIONS AND RECOMMENDATIONS

With regard to respondents experiencing fatigue in their buildings, if the buildings are built in areas where there is a lot of noise (such as traffic noise), this could lead to occupants experiencing discomfort. If the buildings are built and positioned such that in the late afternoon, there is a glare that beams through the building discomforts such as the ones highlighted in the findings. To avoid these effects on the occupants' health and physical well-being, it is imperative to take positioning of not only the building but aspects such as windows, doors and ventilation in the construction of low-income buildings.

The inexplicable headaches reported by the occupants could be dealt with through the avoidance of installing fluorescent lighting in buildings when the building is being constructed and occupants themselves can lower this indoor environmental quality issue through not using or exposing themselves to artificial lighting in their buildings and thus will reduce the occurrence of these inexplicable headaches that occupants experience.

The experience of itching and burning of the eyes in buildings that the respondents reported experiencing is not essentially connected with any indoor environmental quality aspects as this is experienced by contact lens wearers who will have to return to spectacles should the irritation of the eyes continue. There is nothing the construction industry can do to curb this ocular manifestation.

Environmental tobacco smoke is a contributor to the deterioration of the indoor environment especially when the smoking activity occurs indoors as the after effects remain in the building and the second hand smoke causes illness in the building. The construction of the building cannot affect this as this is an occupant's life choice to do although it does have detrimental effects on occupant's health residing in the building.

The combustion during the cooking process releases harmful gasses into the atmosphere which in turn causes chest tightness and wheezing in those nearby. This can be alleviated through industry advice not to use gas stoves indoors.

Cleaning the environment indoors is a means of alleviating the malfunctions caused by the contamination of the indoor air and depending on how much cleaning is done in a building, the more livable the environment is to the occupants that reside in the building and is good practice as the more cleaning is done, the healthier the environmental quality is for the occupants. The respondents reported cleaning but it can be said that the ones who clean their homes more suffer less from health and well-being effects of indoor environmental quality caused from various contaminations that make the building uninhabitable such as dust, dirt and stuffy air. The use of devices such as humidifiers can cause physical health and well-being problems such as humidifier fever and are not advisable to use continually as there are health and well-being effects that prevail from prolonged use.

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Theme: Temporary Housing for Disaster Situations

Planning and design interventions for post disaster temporary housing in India

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ABSTRACT

Natural disasters not only cause dilapidated buildings, but also delay crucial aid for those affected in the event of a disaster and post disaster recovery. Post-disaster housing strategies, which are institutionally well managed, provide opportunities of physical and mental healing of its occupant. The time required occupiers to remain in the temporary housing varies with circumstances. The manner of planning and design of post disaster housing impact recovery of its occupant. World risk report 2016 put India in 77th position in world risk index. The research evaluates the recent natural disasters in India and implementation of its post disaster shelter strategies. For evaluating these strategic interventions, the research selects coastal cities in the state of Tamil Nadu, where post disaster temporary shelter and rehabilitation, was planned and implemented after 2004 tsunami. The tsunami created havoc in Nagapattinam and Kanyakumari district of Tamil Nadu, India. Nagapattinam district reported 6,051 fatalities and many more homeless people. After the Tsunami, the government has taken measures to supply safe, secured and on site shelter provisions. Surprisingly many such shelters never occupied, even after knowing the prolonged time required for rehabilitation. In many instances, the people actually may have to spend years in temporary shelter. This paper aims to evaluate such events. The study investigates these evidences as Indian post disaster shelter strategy against the derived best practices from around the world. This study will focus only on natural disaster and its potential threats to This study is based on the sequential logical reasoning and detailed understanding of facts. Discussions from this study can be further generalised into a comprehensive policy discussion.

1.0 INTRODUCTION

Sendai framework for disaster risk reduction 2015-2030 has given prime importance to non-permanent housing and permanent housing that integrate with livelihood enhancing programmes, food security, nutrition, and education (UNISDR 2015). It is particularly relevant for the local governments, which is responsible for service delivery to the people. Anticipation and preparedness against multi-hazard disaster risks are crucial for

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normalising disaster risk reduction. Hazard defined in the 'Hyogo Framework' for action as, a potentially damaging physical event, phenomenon or human activity that may cause a loss of life or injury, property damage, social and economic disruption or environmental degradation. Hazards can be of natural (geological, hydrometeorological and biological) or induced by human processes (environmental degradation and technological hazards) (UNISDR 2005). At first, communities need to make aware of the probable disasters and potential threats that may occur out of those disasters. Investment in knowledge and attaining ideas from various cases around the world can make a society knowledgeable about preparedness from probable disaster situations. Knowledge from global examples needs adjustment as per the local requirements. Further, an appropriate dissemination strategy among the communities can safeguard it from possible pitfall from disasters and thus make it less vulnerable. Therefore, we need a dual mechanism that supports advanced technological and scientific knowledge among the professionals & academic experts, and an appropriate institutional mechanism that may disseminate their findings among communities, and create a legislative & policy framework. Preparedness against disaster risk solemnly depends on these two traits. Unfortunately, developing countries are always in a dilemma whether and how much to invest in disaster mitigation. This dilemma creates havoc to them. They are neither prepared with adequate knowledge, and nor their community is safeguarded with important skills to avoid potential risks. As a result, strategic policy architecture and legislative framework falls much short to overcome complex post disaster situation. Particularly, post disaster recovery become more challenging for local or regional governments. Their awareness is limited about post disaster recovery, rehabilitation, and reconstruction attributes and methods to attain such attributes. It leads intuitive decisions during post disaster recovery that are prone to error and further aggravates natural disaster into a prolonged manmade calamity. And this time it affects multiple generations. Sendai framework for disaster risk reduction 2015-2030 has identified four priority areas of disaster mitigation (UNISDR 2015);

- To understand disaster risk;
- To strengthen disaster risk governance and manage it;
- To invest in disaster risk reduction for resilience; and
- To enhance disaster preparedness for effective response and to build back better in recovery, rehabilitation, and reconstruction.

This paper will particularly pose questions on post disaster housing initiatives in India to highlight its existing context in comparison to some of the global benchmarks. It will also investigate probable causes for such a condition. As for the research methodology, we have used 'analytical narrative' of the 'case study' for establishing the central argument and discussions. Major limitations of this study are data availability, data accuracy, and delays of the study from the actual event are its major limitations. The next section presents literature review on post disaster housing and its various attributes.

2.0 LITERATURE REVIEW - POST DISASTER HOUSING

Disaster preparedness has links with effective response in post disaster recovery. However, its influence in housing strategy is not much explored in literature. Considering the lacklustre disaster preparedness in India, our initial assumption is that post disaster housing strategy is intuitive. It depends on the scale and damage intensity of the disaster. This raises an important question – what do we actually mean by recovery and how do we measure it? Various possible metrics come to mind. The number or proportion of people living in temporary accommodation, or the time taken to rehouse everyone in permanent housing can measure housing reconstruction process (Platt and So 2014). Identifying housing that is economically feasible or unfeasible for retrofitting are the first logical step in housing strategy. In order recognise housing condition, an organisation needs to be empowered with an approved standard of physical and structural systems. Post disaster recovery is a long-term process that starts with addressing emergency services to secure long-term rehabilitation. It is particularly relevant for housing, livelihood, socio-economic, and human development. Quarantelli (1995) makes a distinction between sheltering and housing. While sheltering refers to a place to stay during the immediate aftermath of the disaster suspending daily activities, housing denotes the return to household responsibilities and daily routine (Quarantelli 1995). Based on this distinction, the four stages are:

i. Emergency shelter - a place where survivors stay for a short period of time during the height of the emergency, which can be in the house of a friend or in a public shelter;
ii. Temporary shelter - used for an expected short stay, ideally no more than a few weeks after the disaster, this may be a tent, a public mass shelter, etc.;
iii. Temporary housing - the place where the survivors can reside temporarily, usually planned for six months to three years, returning to their normal daily activities, and can take the form of a prefabricated house, a rented house, etc.;
iv. Permanent housing - return to the rebuilt house or resettle in a new one to live permanently.

Thus, temporary housing can be defined as an object or physical structure where people reside in after a disaster, a part of the post-disaster re-housing programme, and a place that serves to shelter people from the disaster until their resettlement in a permanent place (C. Johnson 2007). Even if we broadly agree with the above-mentioned distinction between shelter and housing, sometimes it is blurred. It is difficult to set an exact duration for such a shift from a shelter to a house, since housing is not only a physical element, but also a place, which emotionally connects its inhabitants. Temporary housing needs to have the following features (Johnson, Lizarralde and Davidson 2006)

- Organisation in strategic terms: Hierarchy of public or private departments or agencies to be mobilised during post disaster recovery process and sharing of such responsibilities among these organisations;
- Procurement: Financing procurement of large items during recovery process and an appropriate administrative monitoring with public accountability of finance;
- Delivery on site: Location choices of new housing units including on ground preparation to develop these housing units at the new locations;
- Community participation: Extent of participation by the future inhabitants in major decision making;
- Infrastructure networking: Connection of rehabilitated areas to ‘hard’ infrastructure (water, sanitation, drainage and mobility) and to ‘soft’ infrastructure (health service, community engagement, markets, educational services for youth);
- Used by disaster victims: Identification of victims for appropriate synthesis of community members for developing a livable neighbourhood;

In order to understand this practice of post disaster housing in reality, we have gone through two cases. The first case is of the Great East Japan earthquake off the coast of Tōhoku. It is the most expensive natural disaster recorded in the world to date. The unprecedented tsunami toppled sea defences, inundating more than 500 km^2 of land along the coastline. There were approximately 18,500 fatalities. Four hundred thousand housing units were destroyed and additional seven hundred seventy three thousand housing units were damaged. Recovery process was in its initial stage after two years of the disaster. Now, Japan is dealing with a difficult temporary housing situation. Construction of new-permanent housing has taken longer than originally planned, but has allowed for longer consultation process (Fraser, et al. 2013). The first temporary housing units were nearing completion after four to eight weeks of the disaster. Within eight months of the disaster, 75 percent of the 450,000 people who had sought refuge in evacuation centres had been able to move to alternative accommodation (International Recovery Platform (IRP) 2012). Twelve months after the earthquake, 330,000 people were still in temporary accommodation and 500 remained in evacuation centres. The key issue is how long people will have to remain in temporary shelter. People living in Kasai Temporary Housing in Ishinamaki prefecture responded that the air-conditioned containers for shelter measuring $30m^2$ are of high quality, with two rooms, a kitchenette, and a tiny bathroom. People expected to live in this cramped condition for another 3-4 years (Platt and So 2014). In addition, the extent and complexity of landuse change bring new challenges to functioning of urban spaces. People wish to avoid hazardous zone and move to a safer places. But, these new locations may not offer the same kind of living and socio-economic opportunities available in earlier locations. People were accustomed with specific pattern of interaction with their necessity and opportunities including their social interactions. But post disaster dynamics changes completely where safety from similar future threats becomes priority among the surviving people. In Sendai (Japan), people moved away from the coast to high-density apartment blocks in high altitude areas. Many of these people are dependent directly or indirectly on sea for livelihood opportunities (fishing, tourism, trade etc.). This is contentious, as many families want to move inland away from the hazardous zones and continue to explore their livelihood opportunities from sea. It is extremely difficult to attain both safer neighbourhood away from the sea and easy accessibility to sea. The government hoped that changes in landuse, and redefining of housing areas in hazard prone zone as non-residential usages, improving transportation links, and promoting urban centre regeneration projects would influence positively on the prospects of these places as well as make them more resilient to future disasters. The focus is to relocate housing to higher ground and construct safety measures such as high levees and evacuation towers (Platt and So 2014).

Traditionally, hazard affected areas experience sharp decline of population, especially younger population. This population reduction depends on the size and economic opportunity of the city. Smaller cities experience more out migration than bigger cities. Japan is also experiencing similar trend during post Tsunami recovery and reconstruction. Therefore, the imperative might be to strengthen the local economy and address economic and demographic decline. Measures that strengthen existing local businesses, city centre shops, attract new industry, and encourage young people are important consideration during a rebuilding process. Temporary shelter for immediate recovery established very fast. While temporary shelter supposed to be for shorter period, but it tends to extend due to many circumstantial obstacles. For Japan, new permanent housing takes longer time due to its compliant society and longer consultation time. These temporary shelters become the place for recovery and rehabilitation as communities gather for participation and discussion with the government officials and related stakeholders. Safe and secured location nearby to the existing city is primary consideration for choosing such locations (Figure 1).

Figure 1: Layout of temporary shelter at Otsuchi-Kamaishi prefecture of Japan

These are multiple locations of temporary shelter units, and each unit has manageable number of household. It helps both the government and people in long-term strategic preparation. Overcoming physical, psychological and economical trauma is crucial during this period. In order to overcome this concern, each temporary neighbourhood is fitted with community centre, park, medication centre, rehab centre, and medical clinic. The community centre also hosts various evening get together, events, workshops, and meetings to discuss future reconstruction and rehabilitation strategy for the community and city (Figure 2 & 3).

Figure 2: Temporary shelter at Otsuchi-Kamaishi prefecture of Japan

Children and old people who lost their relatives are particularly vulnerable and need special attention in post disaster recovery. These temporary shelters try to support psychological traumas through various kinds of engagement, discussion, talks, and activities.

Figure 3: Community centre at the temporary shelter at Otsuchi-Kamaishi prefecture of Japan

The second case is from Indonesia, which suffered extensive damage from the 2004 Indian Ocean earthquake and tsunami. An earthquake struck 150 km off the coast of Aceh. Forty-five minutes later, the tsunami wave hit Aceh and within minutes, it swept clean an 800 km coastal strip of Aceh. The housing sector suffered about a third of the total estimated tsunami damages. Initially more than 500,000 people became homeless by the disaster. But most were able to return, leaving about 192,000 internally displaced peoples (IDPs) living in tents, barracks or with host families. Of those who returned to their homes a potentially large number are living in temporary structures built from reclaimed materials. Gradually, many people were able to repair and clean up their homes; some have built shacks on their old house-plots; and some have even built new houses. The government, in particular the army did an impressive job of building barracks-style accommodation and coordinating others in a programme of temporary shelters for these IDPs. From the beginning of reconstruction process the Indonesian government and many organisations focused on community led recovery process. Many organisations started discussing strategic recovery options with community members to arrive on specific course of future action. The early idea of a master plan – a top-down blueprint plan where communities would be relocated and where houses and facilities would be built – had given way to community driven development. The shelter programme had a single objective; to get people into progressively better accommodation as swiftly as possible. In the first few days, this meant bringing in tents from across the world so people could move out of crowded public buildings and off the streets. In the following several weeks there was a dual approach of encouraging people throughout Aceh to host displaced families and simultaneously planning a series of “temporary living centres” with barrack-style housing that hold some 15,000 IDP families. Within two months from the disaster, work started on building permanent houses. The early programmes of significant scale were the “transitional house” schemes comprising of prefabricated buildings erected on leased or local government provided land. At the same time, donors and NGOs started planning permanent housing on the site of people’s original homes or on plots identified by the communities. A long- term housing strategy started to emerge. There had been a renewed focus on temporary housing. The communities have urged NGOs and donors to help build permanent houses as swiftly as possible. Housing strategy in post tsunami Indonesia was very swift and insightful. The government’s decision to employ community for long-term housing rehabilitation programme has positively influenced in solving the housing crisis. Contribution of army and other organisations in building shelters with innovative ideas and materials helped into to reduce gross homelessness. Unaffected household and communities extended help in hosting families until the availability of temporary shelters (The BRR and International Partners 2005).

Now, we will explore the case of Chennai to comprehend the initiatives vis-a-vis the global examples. It is debatable to measure the success of housing. For government officials, the indicator is to meet the number of housing supply to each affected household within the stipulated time. However, for families who suffer physical and psychological loss, a house is not good enough. Families look for an environment and opportunities to rebuild their future again. The success of housing programme is measurable based on its capacity to support each family to achieve their endeavours.

3.0 THE CASE OF PULICAT, TAMIL NADU (INDIA)

This paper has particularly studied Pulicat of Thiruvallur district in Tamil Nadu, which was severely affected by the Indian Ocean Tsunami in 2004. It is about 60 kilometres (37 mi) north of Chennai, on the barrier island of Sriharikota, which separates Pulicat Lake from the Bay of Bengal. Pulicat is India's second largest brackish water lagoon with its mouth opening in the Bay of Bengal (Natesan, Rajalakshmi and Ferrer 2014) (Figure 4).

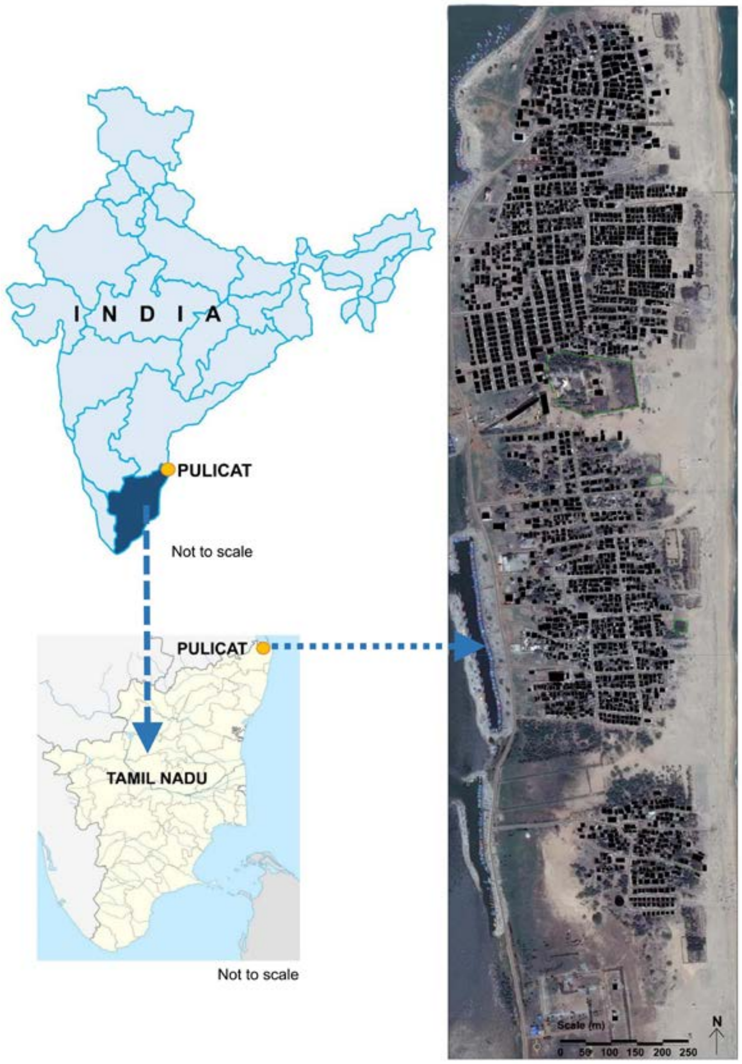

Figure 4: Pulicat village morphology and its location in India

During the tsunami, people were stranded in the island with no road connectivity to move out to a safer place. Significant destruction took place in this village with many lost their shelter completely. After a decade has gone by, the destruction is little less visible. Yet, some distinctly visible signs are lying on part of this village (Figure 5).

Figure 5: New housing by the Government over the ruins in Pulicat village, Tamil Nadu, India

The figure above shows damages of tsunami and housing units at the same locations. For Indian case, distinction between temporary shelter and permanent housing is blurred. There are not many efforts to build temporary shelter. People spend their time in relief camps, supported by the government. Safety, security, hygiene, and cleanliness are questionable in these relief camps. Resource constrains, knowledge limitation, and organisational motivation are the deterrent for effective temporary shelter strategy. But permanent housing units are constructed much faster than that of the case of Japan. The government accomplish this feat by eliminating consultation and community participation process. For the government, land acquisition and fund are the two major obstacles. Once fund is secured and public land is available, permanent housing construction become easier. Figures 4 and 5 show similar government aided permanent housing supply. These images show the nature of intervention and brutality from the government in failing to comprehend the agony of these communities. Hundreds of one bedroom housing unit of similar appearance built haphazardly without any consideration of family size, structure, need, distance from their socio-economic engagements, cultural preference etc. As a result, most of these housing units lie vacant today. A similar point made by Lloyd-Jones (2007), commenting on post tsunami recovery in Tamil Nadu. People from poor communities, displaced by disasters, face multiple uncertainties. Families who have traditionally depended on fishing are opposed to relocation away from the places they formerly inhabited. Displaced people worry about losing land, and restoring their livelihoods. In Tamil Nadu some of the newly-reconstructed houses remained unoccupied because they failed to meet basic needs and cultural practices, or because they just happen to be in the wrong place (Lloyd-Jones 2007). Authors captured some of the shelters that are built by fisherman communities who abandoned government providing housing units and built much weaker structure to live. These shelters support their ardent economic and cultural requirements (Figure 6).

Figure 6: Shelter built by the community in Pulicat village, Tamil Nadu, India

4.0 DISCUSSION & CONCLUSION

Post-disaster recovery inevitably involves tension between speed and deliberation. Speed is important in order to keep businesses alive, rebuild infrastructure, and provide temporary and permanent housing for disaster victims (Olshansky 2006). In Japan, the long-term policy is to define a hazard zone and to move people up and away. Short-term recovery efforts must aim to minimise the time needed for people to be rehoused safely and re-establish livelihoods. During, this ‘transitional’ phase it is critical that communities are informed about longer-term plans to reduce anxiety and frustration (Platt and So 2014). Post disaster recovery involves a large number of organisations from different governance hierarchy. Coordination among these agencies is troublesome. It is extremely difficult for all countries and there is no unified answer to it. Public consultation and community participation for long term rehabilitation is key for strategies that meet aspiration of local people.

For India, the challenge is that local community sometime lack to visualise their aspirations and requirements. Youth do not participate much in consultation or decision making arena. Therefore, their views are neither heard nor considered during the decision-making process. For short-term recovery, immediate support for survival dominates strategic decision. Distinction between temporary housing and permanent housing is blurred for Indian cases. Most of the time, people spend considerable amount of time in temporary shelter before moving in to permanent housing. There is no real vision or standard to plan these temporary shelters. Politically, attaining the number of homeless people under some kind of shelter is important achievement. Administrators and organisations are least interested in providing the real necessity of the community who are put together for an unknown period. The victims often lack confidence in demanding their due from the government and different authorities. There is almost no understanding of the physical, economical, psychological aspirations for these people among the organisations that are responsible in reconstruction and recovery.

In India, permanent housing construction is faster than many other examples around the globe. The examples are evident that attaining number of housing units for reconstruction was important milestone. Many of these housing blocks are provided without even a proper approach road and basic minimum infrastructure. These housing units fail to meet social and economical aspirations of people. Many of them are abandoned or put to different usages. A better way forward may be to prepare specific planning for temporary shelter where people spend considerable amount of time after disaster. As seen for the case of Japan, these shelters can offer platforms for future planning and long term rehabilitation process. But the process needs to be faster for these families and particularly for the youth and children. Otherwise, they may lose important phase of their life and lack in nutrition, education, knowledge, or training ability. Role of organised institutions like armed forces and other communities are also important, as experienced in Indonesian case. The government may also put forward incentives for households in unaffected areas to host people from disaster-affected areas during the initial phases. This will reduce the number of homeless people and provide the victims with a moral support.

Finally, to answer the question on the meaning of recovery process and its measurement; we may point out that the abandoned houses of the coast of Tamil Nadu shows a gross failure of post disaster housing strategy. Speaking to the communities, we felt that those who are using these housing are compelled to do so. In some cases, part of the family is staying in these shelters because of the small size of shelters. The communities mentioned livelihood aspirations, social networking, and future growth concerns for leaving the government provided shelters and building lower quality shelters on their own. In response to our concern of the safety of their existing housing units, the communities responded that they are aware of the similar threats in future. They also sight lack of available options for choosing such unsafe shelter over government provided housing units. Their existing shelter provides opportunities for pre-fishing and post-fishing activities in large groups, knowledge and information share between different fishermen, and community bonding.

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Modular integrated smart house: prefab for performance and environment An innovative research experience for Italy

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ABSTRACT

The Politecnico of Milan is making research on a modular, prefab and highly performant new construction system.
The basic idea is to design all the entire construction as a pre-assembled "machine" whose shell is thought and integrated with plants and all performances are pre-defined and pre-assigned, re-using HC maritime containers as structural frame.
Containers have been used for constructions for many years, but most of these projects are handmade or container exhibited. Our idea is very different: container is used at its best, pre-configured it in workshop and without showing it. The container is only the basis, reinforced as little as possible, on which we have all the operations in workshop; then the pre-configured containers are brought to the construction site and assembled, with structural active junctions, the insulation and the wrapper is put on the outside of the sheet.
High performance buildings can be carried out only with high defined and industrialized construction system: quality can be reached only with controlled elements and operations, without taking any decisions or any fundamental operation on-site.
We have mentioned "machine": every part is absolutely active interconnected with all the others, as for example the structural joint in which we integrate sensors showing, after an earthquake, which elements and with which intensity have suffered damage and need restoration. Furthermore, the skin is integrated with plants because energy management starts from wrapper and gets to the generator and all the elements are designed together and strictly related, depending on climate, latitude, solar radiation and energy target (nZEB, off-grid, ...).
This type of construction can get its best in modular repetitive aggregations; it is perfect after emergency: container house, in this case all pre-finished in workshop, can be easily and quickly transported everywhere (by truck, by train, by ship) and set in few hours.

KEYWORDS

Prefab, container, integrated energy, structural seismic performances, smart building, emergency

PREFAB IN EUROPE: SCENARIO AND TRENDS

The building sector in Europe is rapidly evolving and amounts to, contributing the financial crisis, the new trends in real estate business both in terms of performance demand and forms of living space using, as well as costs, of turnover, technologies and constructive techniques, products, components and systems. Testing, daring, going beyond the stereotype has often generated seemingly simple but shuttering solutions, proved through the results of research on industrialization and new building techniques for residential construction since the first half of XX° century (…)[1]. This innovation wish leads the proposal of an industrial modular construction system that uses prefabricated elements transferred from another production sector to the construction one, for the realization of single and multi-familiar residential buildings with high energy performance (from NZEB to OFFGRID) at current cost and with high guaranteed performances.

[1] From CIAM to CSHP US competition (Smith 2002), up to national researches and experimentations on prefabrication of the famous neighborhood QT8 in Milan.

Regulatory framework for the construction sector

The need for sustainability, continuously practiced and consciously assimilated, which goes together with the introduction of the 7th requirement for construction[2] products poses major issues in terms of construction systems, durability, recyclability, clean and safe construction site. For some years now, in Europe, it is compulsory to think about the building in terms of global life: this has led to consider not only the intrinsic durability of materials (for which our continent has thousands of years of tradition) but also and above all the obligation to design end-of-life buildings. This shows two consequences: to reduce the environmental burden generated by the dismantling of buildings and, thus, diminish the costs for the community. For the first time, the legislation requires that any project has a strong focus on the demolition phases of the building, resulting in a series of design choices that, from the very beginning of the design of the building itself, are oriented towards the principle of the 3R: Reduction, Reuse, Recycling. Efficiency in the construction industry also passes through to the implementation of building materials and new conception plants: at the same time, it is important to analyze the whole life cycle of the product and of the all intervention to decide on the policy criteria to be adopted. This trend has certainly had an active effect on the way of designing, but even more on the way to construct buildings, which can be synthesized in some key principles:

- R1 - the need to reduce construction materials (in absolute terms, but above all in terms of gray energy and intensity of matter) will lead to the gradual rejection of traditional techniques that use massive and wet materials;
- R2 - the need to reuse materials obliges to choose second (not brand new) products that can be used as they are, without the need for heavy transformation or machining. This applies both to the production phase and to the demolition of the building: in this regard, the demolition will be replaced by disassembly, as it is only using dry construction techniques that reversible processes can be made and from which to obtain products to be used again;
- R3 - similarly to the concept of reuse, recycling pushes to choose non-raw materials derivative products on one hand, but also assembly products and techniques that, at the end of the useful life of the building, can give rise to products that are easily disassembled and then sent to the new regeneration and recycling cycle.

For the future, this new Europe approach will force the market into a new way of designing and managing the entire production buildings cycle, starting with the construction site (which will be dry and clean), the management (easy and intelligent thank to the building facilitate inspection and replacement of components), the decommissioning (where the building can be disassembled and become a source of secondary stuff to reuse). The proposal we herewith want to illustrate is grafted in this need to reduce waste and resource conscious use: the container can be considered both as a resource (new) and as a second resource (reuse or recycle). The container is nowadays an emerging system, in terms of being a "visible" object and a "hidden" structure. The countless cases of experimented, realized, and inhabited container houses around the world confirm the previous statement (Garrido 2015).

Main European Policies

In order to face the extreme use of fossil fuel, despite the lack of availability in the UE territories and in order to comply with the Kyoto Protocol, the European Community has issued Directive 2002/91/CE "Energy Performance Building" on energy efficiency, on 16th December 2002, whose purpose is to define measures, guidelines and specific actions meant to increase the energy efficiency of buildings, and introduce the obligation of energy certification for buildings or apartments in the case of new construction, sale or lease. So far, the management of energy demand in the residential and tertiary sectors represents about 40% of the energy used among the EU state members: therefore, it's fundamental to promote energy improvement. In Italy, this operation took place through the energy certifications (ACE), introduced by DL n.192 dated 19th August 2005 which states that "Implementation of Directive 2002/91/CE" in article no. 7, now transformed in energy performances certificates (APE) through DL n. 63 dated 4th June 2013".
The same relevance is given to the notice "EUROPEE 2020 - A smart, sustainable and inclusive growth strategy" dated 3rd March 2010. The ultimate aim is the improvement of EU competitivity through

[2] REGULATION (EU) No 305/2011 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 9 March 2011 laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC.

maintaining the social economy model and significantly increase the efficacy use of its resources. A conspicuous growth is expected: smart, through the development of knowledge and innovation; sustainable, based on a greener economy, more efficient and competitive; inclusive, aimed at promoting employment as well as social and territorial cohesiveness. In order to achieve these goals by 2020, the UE community aims to reduce greenhouse gas emission by 20%, to bring renewable energy amount to 20% and increase energy efficiency by 20%.
All this will also allow you to get rid of submissions to the use of dirt fuels. These goals are better described in the "guiding-light" strategies; including a "resource-efficient Europe – a guiding-light initiative under Europe 2020 Strategy" dated 26th January 2011. The document highlights the possible synergies that could positively impact on building energy efficiency, produce better air quality, health benefits, increase industrial competitiveness, new jobs, finances to invest in social and choose less infrastructures.

New trends in housing markets in Italy

The construction industry in Europe is being renewed, albeit tiringly. Marked trends clearly show that only industrialized systems that guarantee certified products and certified buildings support the challenges of a global market, also in the construction industry. If this is true in Europe, in Italy its intrinsic and historical features still make it a sector that needs to recognize, regenerate and renew the project management modes in order to make the process efficient and effectual both in the relationship between the involved actors and the forms of designing, realizing, managing and disposing of the architectural work. The sector is faced with new cultural and operational challenges that make it more competitive and capable of meeting different needs that must find adequate, appropriate and timely responses: trends for the next few decades require smart buildings where large masses of data will be put on the network and in which realization times and reliable performances will be the real discriminant that will drive the investments and the market. Likewise, design must be able to renew, through integrated knowledge management systems (BIM), anticipation of decisions, constant horizontal coordination of all involved actors. We are confident that even in Italy, that containers use can be a viable and competitive constructive strategy: products are easily available; they have easier handling; it is a standardized system and therefore identical all over the world.
That's not enough, it has been seen as a constructive system that is making a tendency in the field of luxury villas, as well as in social housing (see examples below). These conditions induce to seek innovative solutions also based on the experience at international level that can be stimulated to spur the Italian market (now without significant real experiences) to adopt this system, and in turn affect overseas markets in the direction of ever greater energy performances.

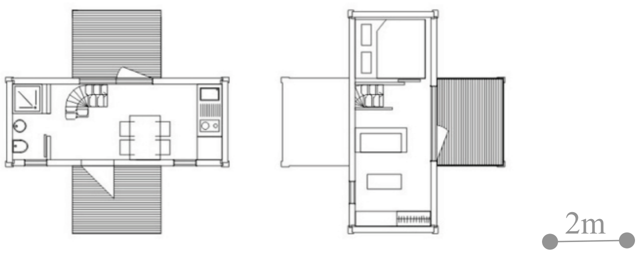
Some significant case studies of housing built with containers

Some examples of houses built using containers are extremely significant for their different use, disposition and exploitation of the module as a basic element for building. The cases prove that container module utilization is highly flexible. Indeed, it can be used with more "traditional" or extraordinary results without or with added structural portions.

The table below demonstrates multifunctionality and functionality of the system.

The module as a sorting element: Conhouse 2+, J. Knotik, Trebnje, Slovenia (2008)

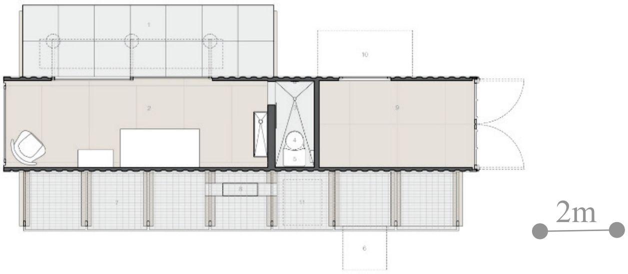
It consists of 2 20' containers placed on each other on the cross, with the possibility of integrating the housing unit with the addition of other container modules. In this project, the container represents a kind of structural grid, being the only structural element that makes up the structure, which articulates the entire living space.



Outside view. Plan (source: http://www.humble-homes.com/2-a-container-home-by-conhouse/)

The container for a sustainable and facilitated project: Container Guest House, Poteet Architects, San Antonio, USA (2012)

The project is used as guest house. The emphasis was placed on sustainable strategies: firstly, recycling a "one-way" container for new and permanent use. The green roof is hold up from the top of the container, providing shade and airflow to reduce heat gain. The back of the container is screened by wire mesh panels that will eventually be covered with evergreen screws. Finally, the container "floats" on a base of recycled telephone poles.

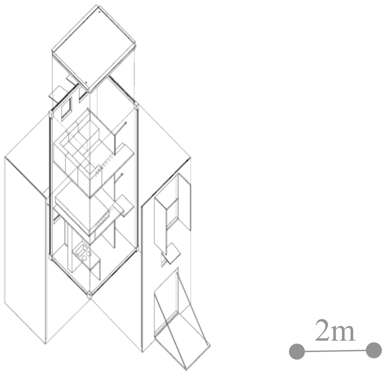



Outside view. Plan (source: http://www.archdaily.com/127570/container-guest-house-poteet-architects)

Use of containers for an easy-to-install system: Homebox 1, H. Slawic, everywhere (2009)

It is a project that aims to create a kind of transportable house that can be laid in any environment. In this case the container is laid vertically (further possibility) for the realization of the whole house that grows in height. The obtained system can be easily transported by truck (being a single container element) and moved by crane to be positioned anywhere the buyer desires. The structure is hidden outside by means of a wooden covering. The ground support is made by means of simple supports with plates.

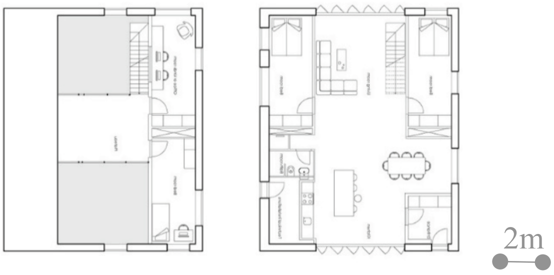




View of the transport of the module. Exterior view. Axonometric split of the structure (source: http://www.slawik.net/images/bautenundprojekte/pdf/Slawik_HomeBox1_projekt%20paneel_EN.pdf)

Using the container as an "invisible module": WFH House, Arcgency, Wuxi, China (2012)

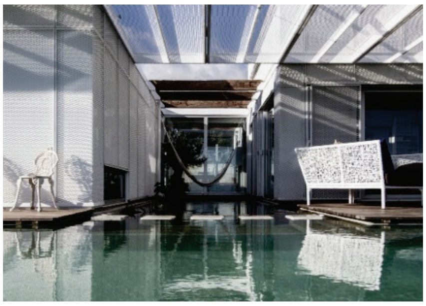
It is a dwelling made of 3 40 'containers (2 of them overlaid) with a metal frame in the middle, which is covered by wood and that creates the central open space of the house. In this case, the container structure is completely hidden outside and inside; its use is purely structural. The presence of "other space", in addition to the containers, guarantees the possibility of having a more flexible use of the space of the house as well as having different internal space configurations.

Outside view. Plan (source: http://arcgency.com/wfh-house)

The container for the "luxury villa": Tarifa House, James & Mau, Cadiz, Spain (2013)

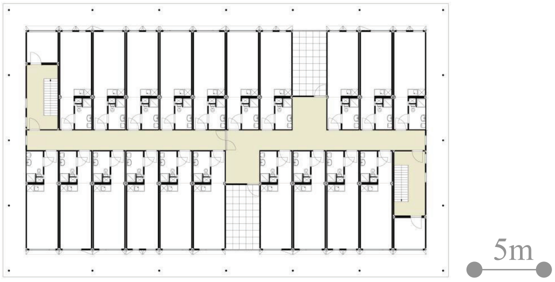
It's a dwelling where the use of containers as a basic structural mesh is clearly evident; design in based on prefabrication in order to ensure easy and fast realization, the use of sustainable materials and renewable energies, such as biomass and solar energy. The settings of the dwelling are made by the combination of one or more container modules, whose presence is not hide externally but, on the contrary, is made iconically explicit.



Outside view. Plan (source: http://www.jamesandmau.com/en/#/proyectos)

The container for social housing and typed residences: Qubic, HVDN Architecten, Amsterdam, Holland (2006)

The container finds its maximum sustainability (economic, environmental, social and institutional) in typed residences, where the residential cell corresponds to the container itself: in this case, the economies of scale, the ease of construction, the functional/constructive/management modularity are evident. This is certainly the utmost expression of the intrinsic potential of the containers.



Outside view. Plan (source: http://www.hvdn.nl/2111/projecten/0342wte.htm)

From the aforementioned cases, it is clear how the possibilities offered by this constructive system are varied and contemporary: our research lies within this scenario, with the stated purpose of using the container in the most coherent way to be able to exploit maximum intrinsic and design potentiality.

THE PROPOSAL

Using a container, even in Italy, as a constructive system, has undoubtedly competitive advantages. In drawing up the design proposal we want to proceed by establishing interpretative/operational macro-categories with which to tackle the various aspects of the project in question.

- <u>Usage</u>: it is suitable for any *climate cluster*, depending on the type of thermal insulation and plants; particularly suitable for the use of *dry technology*[3] and solutions with industrial components and techniques; it can be considered as a *second resource* (because it has already been used as a ship-container once at least) and *first resource* (because once the building is dismantled, it regains full autonomy for being used again); it can have, as infinite cases already realized all over the world show, a very high degree of *versatility* and *customization*. In addition, the container lends itself to solutions for highly diversified utilities: from prestigious villa to students' house, to social housing.
- <u>Module</u>: *structurally effective* (with significant advantages in terms of stability, load distribution, simplification of the structural scheme, redundancy, seismic behavior); *indicative* (the container acts as a grid that constitutes a geometric reference of the project with the function of prevailing rhythmic scanning, upon which to engage the entire project with significant design and constructive advantages[4]); *spatial/token* (the spaces obtained have a surface defined by a finite number of modules belonging to the considered pattern, so that the buildings are born as an addition of pre-arranged space modules, benefiting both the design, the realization and the formal equilibrium); *productive* (linked to

[3] As set by the European Union in its recent decrees on sustainability (see section 1.2).

[4] Think of the many houses built by F.L. Wright in which he imposed a basic grid (Rosembuam or Herman house for example).

both out-of-production individual components and to the construction of the yard - with the possibility of greatly simplifying assembling modular parts). The module/container, therefore conceived as a material and immaterial /cultural element, means that its overall quality is not the mere algebraic summation of the individual restorative qualities of the individual used products, but it expresses in the quality of the relationship. Therefore, if the project is able to adequately handle complexity, the sum of the parts can be greater than the quality of the individual components, also thanks to the high degree of multifunctionality inherent in the system itself, which is well expressed with flexible design solutions in the choice of the final solutions.

- Setting up: the proposal here presented is based on the absolute need to simplify the realization phases at best, while at the same time ensuring the best possible use of the container resource: the structural box element must be used in the best way to maximize its mechanical characteristics; as well as the joints between a container and the other are the main points where the project's sustainability (including economic) is articulated: the connections should use as widely as possible the widespread serial components already on the market and use ad hoc components only if these are strictly necessary and do not have costs higher than the standard ones. By doing so, you get an intensity of use of the components and materials that delivers high performance at low cost[5]. It is also not to be forgotten that all containers follow strict ISO standards of implementation and are therefore all identical (permissible tolerances are in the order of cents of millimeter): this allows, once the most suitable design solutions are identified, to transfer them virtually in every part of the world.
- Targeted design: mandatory to identify "typical" solutions that, as a necessary feature of any prefabricated building, can support the need for anticipation of decisions in order to ensure a lasting result that is sustainable and that, avoiding any set figurative seriality, has a very high degree of customization and is easily maintained, transformable, manageable. This is only possible if the design is prompted by the search for techno-typological flexible solutions, the use of multifunctional solutions and products, and the definition of the best spatial configurations that maximize the space/container ratio.
- Easier and sustainable realization: the high availability of containers[6], the ease of handling and the close attachment that the use of containers has with the industrialization, understood both in the process of making the work (easy installation, etc.), both in the design management process (not least through BIM systems), make the container one of the most interesting transfer building material of today market.

This idea is placed in the Italian market where the trends of prefabricated houses (mostly wood) is growing up. If, however, on the international scale there are many cases of containers used in permanent housing, in Italy, currently, we have some commercial, exhibition, play and entertainment realization compared to a sporadic use of containers for temporary use (post-calamity, holiday villages, mobile offices); such experiences are conducive to studies and experiments aimed also at permanent living.

High-performance housing: basic principles

The research subject of the work which involves, in addition to the Politecnico of Milan, various leading Italian and multinational companies, is based on the use of containers as a building structure, also multi-floor, with external glass cellular insulation (chosen to maximize the features of the container weathering steel), customizable interior and exterior coatings, ad hoc design systems to optimize the energy / space ratio / structures, dry foundation with screw systems, to build permanent housing buildings (from single-family villas, student house, hotel, social housing). In the following description of the project, four design criteria, the result of this research, identify the basis for prototyping and subsequent marketing of the system.

[5] See, for example, the case of Villa Oruga, a very beautiful example of a container-like house but which uses the container more as a pretext than as a real constructive system, failing to take full advantage of its potential, betraying the idea with which a container is born: maximum exploitation of materials, economy, adequate form to the purpose, ...

[6] Italy is a major importer of goods that arrive mainly by ship, in containers produced in China: once emptied, they are often stacked to tens of thousands in the ports or nodes of interchange and often find no second job.

Structural Optimization: 1st design criterion

In Italy, a high percentage of the territory presents high seismic hazard and has therefore been subjected to particularly restrictive legislation in terms of new buildings, in order to deal with earthquakes and to safeguard human life. The project engages in this scenario. Below you have some considerations to identify the general guidelines on the use of containers for the construction of civil-use buildings of a limited number of floors (two or three - as the increase in the number of floors would require specific dynamic models and therefore general design rules could not be defined) in their integral configuration (parallelepiped closed on the four sides) or with partial or total removal of some wall elements up to its simple chassis reduction, with the stated aim of identifying the sustainability (especially economic) range of the system: an intact container can resist high intensity dynamic action, but we have tried to determine to what extent it is possible to cut and modify this structure so that, without excessive investment of added material, is still a valid and safe object for the building industry world (even in earthquake conditions). In the absence of direct experimental data on partial or reinforced units, we started from the design requirements prescribed by international standards and from simplified calculations. Here are some general considerations about the container in its commercial configuration.

Vertical Load Limits: containers are tested by applying vertical loads applied to the nodes of a complete 40-foot cell, equal to 97t; for the normal loads of a residential building, the maximum competence load transmitted to a corner column of a 3-storey building made up of the same containers is in the order of 10-12 t in operation, and therefore 14-17 t at the Ultimate Limit State (ULS); the column at the container door, considered as isolated, by theoretical computation, is capable of bringing to ULS about 25 tons.

Therefore, the expected loads for a three-story building are well below the limit values of the vertical angular structural elements. Transferring of vertical loads to the container edge nodes is ensured by the "wall-beam" of the side walls; the introduction of doors and windows, necessary for the functionality of the building, may compromise such scheme. We have two available alternatives: to ensure the direct transmission of vertical loads up to the foundation; to perform a Vierendeld beam function through the arrangement of vertical and horizontal elements.

Openings in the walls: full-height wall openings for creating glazed walls, outdoor passages, etc. without reinforcement of existing structures: at a first examination, it must be limited to spans less than 3.5-4.0 m. It is necessary to ensure that the compromised wall-beam must be reinforced along the free borders by suitable C-beams, and to ensure continuity in the propagation of vertical loads to foundation.

Horizontal load limits: horizontal loads (due to earthquake and wind): horizontal test load is fixed by the standard to 15,000 daN. Strengthening provided by diagonal plates (St. Andrew cross) and not too small dimensions vertical elements (e.g. rectangular tubes 100x50 mm or similar) can provide high resistance, in excess of the capacity of the ground resistance underneath the bracing.

Door opening: in this case, preserving the wall-beam operation is not possible; it is necessary to carry the loads down to the foundations with appropriate strengthening elements and try to give vertical continuity to the openings.

Single frames: the use of three-dimensional frames without filling walls requires the following observations to be made: for columns, the carrying capacity of the elements placed on the edges of the commercial containers is generally sufficient from the point of view of the steel sections; measures must be taken to prevent local instability; the floor supporting beams must be reinforced by adjacent elements; no resistance effect to horizontal loads can be entrusted to the frames.

"Smart Living": 2nd Design Principle

The project was born out of the idea that "smart" cannot be just plant engineering: smart must be the project, starting from the modularity and the use of pre-ordered and pre-fabricated elements, and from the supporting structure (in this case the container). Smart must be the edification, as well as the use, the management and the entire lifecycle of the building in which the constructive laths of the traditional building site are eliminated, through the realization of most operations in controlled workshops. Starting from a pre-existent load-bearing structure, you can already put building control and management systems into the workshop[7], starting with building constraint system monitoring devices: we are going to test sensors that can monitor and reveal any structural anomalies in real time, also as a result of seismic events. Smart requires a team of companies who, from early design ideas, has the knowledge to work together on a project

[7] From companies used to work on machines and not on buildings.

that, apparently simple, requires complex synergies and integration. Smart because we know that all information must be processed simultaneously and in a coordinated way: hence, the need to develop appropriate software designed for this application. The system also represents a controlled environmental impact product at every single stage of the product life cycle: production, management, recovery, due to the use of HC20' and 40' container modules applied according to the logic of the circular economy and used as a non-visible structural system, just like traditional systems. Choosing the recycling of container modules (weathering steel HC containers) as construction systems represents a cost reduction of about 20% compared to the construction of a traditional chassis structure in R/C. The container is a solid, flexible, recyclable, resistant, durable, easy-to-carry and low-cost object that meets the requirements of the 7th Essential Requirement introduced by the European Regulation CPR 305 / 2011 issued on March 8, 2011.

Energy efficiency: 3rd design principle

Since space/energy binomial is the basis of this project, two are the performance scenarios in which it has moved: NZEB and OFFGRID. They are characterized by very similar needs despite some important differences. In the first case, it is necessary to comply with the constraints under the current European legislation, which classifies the building as a Nearly Zero Energy Building or almost zero energy building with an extremely low energy content from existing network systems (electricity, gas, gas oil and other non-renewable sources); the second case is a further challenge as, in addition to achieving the above mentioned results, the structure must be able to store energy from the outside (when it is available to a greater extent than instantaneous demand) and release it in periods when it is no longer available and it must also be able to match the amount of energy needed every time of year. This condition is not strictly necessary in NZEB buildings, since it is possible to use network power services (electricity, gas) to cover not enough self-production. The OFFGRID buildings are generally NZEB buildings (they must have very little energy needs) but they must also have the ability to store all the energy needed to fully meet the energy needs. In order to limit the size of the storage, the need should necessarily be limited or “monitored” and “spread” the consumption of energy: this is the key to the success of a OFFGRID building. For the application of these studies, energy can be mainly stored in two forms: thermal energy or electricity. The first one has the characteristic of being less "noble": not all thermal energy is completely convertible into another form of energy (mechanical or electrical so that I cannot simply run a bulb or blender using heat energy) and so it has a limited efficiency use, but generally requires simpler materials, which can be met by quantity to ensure adequate energy storage (e.g. using water or subsoil, if conditions permit). Electricity, on the other hand, requires storage with batteries or with kinetic or pneumatic systems, the cost of which is generally much higher than the stored energy capacity, but with a wider usage flexibility than pure thermal energy storage (I can run bulbs, blenders, but also heat up with heat pumps or wipe my hair with a hairdryer). In some cases, some invariants are shown: in any case, an adequate amount of electricity (on a daily basis) is required for the operation of all electrical appliances in a dwelling, from the fridge to the tumble dryer. The basic assumption is the use of high efficiency appliances, triple A and higher classes and a correct use by the user (LED lighting, induction plate for cooking, heat pump dryers, washing machines with direct dual water supply). In Italy, in these normalized conditions, in the typical use of a 4-people family, daily electricity consumption is estimated to be about 10 kWh for all non-thermal uses (from cooking to air conditioning and entertainment). This value is to be regarded as conservative, in fact it is possible to reduce this requirement but we have taken the maximum value for caution. A lower result can be obtained by using extensive home automation, avoiding waste (switch-off lights depending on presence sensors) or the use of intelligent home appliances, such as double-load washing machines (hot and cold water) used at the right way at the right time (it’s also necessary to reduce the consumption of domestic hot water). The main source of energy supply is the solar one, always available; therefore, in any case, an adequate capturing surface must be provided to convert solar energy into thermal energy or electricity (photovoltaic). The installation methods, i.e. the area available for allocating photovoltaic panels, inclination, azimuth, strongly affect the producibility of these systems, which can be integrated with multifunctional tracking systems (solar tracking panels). This attention must be great in those installations in which the volume served is wide but the capturing surface is reduced (multistory) or when the maximum solar radiation does not match with the maximum energy requirements (mountain climates). A second resource, if available in sufficient quantity, can be considered the wind. Finally, in cases where solar or wind power resources are unavailable (e.g., in areas where the groundwater remains or in any case shadows from adjacent elements), other energy sources must be used: in the specific case, the "ready to market" solution is considered a system consisting of an electric generator powered by a renewable resource (such as bioethanol or biogas) and a heat pump connected to the generator itself. A thermal and/or electric accumulation system allows you to "decouple" the two energy outputs and thus optimizes the overall functioning of the system.

Techno-typological and Techno-Morphological Flexibility: 4th Design Criterion
One of the basic assumptions for an effective use in residential area of the module container is that it is conceived of techno-typological flexibility as a guideline for guiding design and constructive choices in order to maximize economical use of resources (time, energy, products, processing, etc.), durability and maintenance, inspectability and time-transformability (just some examples). You must consider modules' configuration and combination in order to identify cost-effective assembly rules that maximize space and minimize costs and empty spaces so that it is possible to provide a compilation repertoire of the module to show the wide range of combinatorial flexibility. The aggregation of the modules can also generate other distribution orders where the containers, visible, positioned along the perimeter generate a large central volume. The different ways of using the module express a first design approach in which the "other space" prevails over the physically one defined by the container, utilizing it as a "box in the box". Another characterization is the protruding use of modules from the perimeter of the building, which demonstrates their potential usefulness even in the expansion of existing buildings. In addition, we have made studies and experiments on functional islands and functions to provide clear and coherent indications on the liveability of the container module in order to better target the project area. This study allows the verification of the usability, flexibility of use, connections, the positioning of the window frames, etc., both within the single module, and in the possible aggregations of the various modules. In addition, these aggregations, starting with the first design criterion (structural optimization), have taken into account the need for insertion of cutting-edge walls (the true key to success in a seismic-resistant system), yet demonstrating the functionality and leavibility.

THE ANALYSIS FOR THE PROJECT

Swot Analysis
In order to better assess and describe the design idea, we carrie out an accurate SWOT analysis.

STRENGTHS - **Innovative results** - **Increased know-how and influences between branches** - **Easy replication of the system**	WEAKNESS - **Lack of structural regulation** - **The need of specific technical and plant solutions** - **Difficulty in coordination between partners**
OPPORTUNITIES - **Cultural, operative and normative evolution** - **Industry 4.0** - **Real estate market growth**	THREATS - **Negative perception of container houses** - **Current regulation too strict, because it's tied to traditional solutions** - **The need of a proper structural control**

The *strengths* identified are the following: a controlled financial exposure and enhancement of existing know-how, understood as traditional knowledge, integrable with innovative technologies; the aggregation of existing technologies for an product with high flexibility of solutions; the need for qualified manpower for workshop machining and site assembly; the contamination of productive sectors and the creation of a business network between different sectors; the availability of containers and their use as a first/second resource, with easy handling, high availability, durability; and ultimately the definition of design strategies for the replicability of workshop and site work.
The *weaknesses* found in the analysis, however, are: the undisputed definition of the container system in the world of structural regulations for buildings, which can be overcome by the preparation of a structural safety assessment tool whose result is recognized as valid for the respect of compulsory legislation and a

monitoring and reporting tool for the underlying vulnerabilities in use; the need for a specific design of technical-plant-structural solutions not available in current production, mitigating through innovative proposals for upgrading existing and consolidated ready made products; finally the possible difficulties in networking of different chain companies can be mitigated through a conscious direction and a design that knows how to identify and anticipate any critical decision at the beginning of the design path.

Opportunities are as follows: the evolution of the construction sector in which new trends emerge in terms of performance requirements; a period of new cultural and operational challenges that require an appropriate competitive capacity to meet differentiated needs with adequate, suitable and timely responses; the transition to Industry 4.0[8]; the need to reduce waste and the need for a resource conscious use; the growing property market for constructive nonconventional building solutions; the maintenance of the high-performance, certifiable and certified housing market; the normative evolution, advanced and innovative structural / energy / environmental / functional / functional / usability and maintainability technical solutions; tax incentives for self energy consumption (purchase of batteries).

The emerging *risks* are: a generalized view of a negative perception of "living in a container[9]" with problems of acceptability, an easily overcome problem as it is used as a structural system visible unless the customer chooses; moreover, as regards the acceptability, it is a matter of fact that it also passes through the degree of knowledge and dissemination of the product by those who have to choose and decide and from the ability to produce knowledge by those proposing it; the existing regulatory apparatus is shifted to traditional constructive techniques and to rigid and predetermined dimensional relationships requiring the use of certifiable or certified components and authorized for structural and anti-seismic verification; control and validation of structural suitability for residential use, mitigable through specific calculation and monitoring (also remotely); any specific local rules (e.g. environmental restriction), which is a mitigating condition from the flexibility of identifiable architectural and energy solutions; the common perception, now dominant, which considers only the wooden house as "ecological", that is an easily overcome idea, through a timely verification of the ecological impact and disclosure of the results of experimentation.

Container Characteristics and Reference Standards (in particular concerning residential construction)

It is necessary to highlight and analyze container aspects that may affect safety: the use of internal and external paints for any harmful emissions; the possible presence of impregnating wood flooring for any harmful emissions; and the anti-seismic legislation.

Primers and paints: from the documentation in our possession the container is painted internally with specific products.

The painting cycle consists of numerous layers, specific for 3 categories: outer sheet, inner sheet, wood. As for sheet metal, the painting cycle can be synthesized: epoxy zinc coat, epoxy middle coat, modified acrylic finish and acrylic topcoat. Specific investigations were carried out to analyze and evaluate the presence of volatile organic substances present in the air due to container itself. Based on the results of the carried out tests, it has been found that the volatile substances contained within the container are absolutely equivalent to those in the surrounding air. There are no significant differences between indoor and outdoor; in some cases the values are lower in the container than the outside.

48h Esterno	μg/m^3
Idrocarburi alifatici	18.1
Aldeidi e chetoni	4.6
Benzene	0.8
BTEX	7.2
Aromatici	11.4
Clorurati	4.4
Acetati	1.6
Alcoli	2.8
C12-C20	120.7

48H Interno	μg/m^3
Idrocarburi alifatici	18.9
Aldeidi e chetoni	9.2
Benzene	0.6
BTEX	6.6
Aromatici	10.1
Clorurati	3.7
Acetati	1.4
Alcoli	2.1
C12-C20	147.5

Tab. 1 Analisys results: external (left) and internal (right) (source: tests carried out by the Chemical Laboratory of the Politecnico di Milano LAC.CHEM.POLIMI.IT)

[8] The development line that the Italian government has identified as fundamental, in which new technologies must deal with transfers, hybridizations and contaminations between real manufacturing and merchandising sectors.

[9] This typically Italian problem is due to bad and not completely correct information from past experience (see last paragraph).

No measurable presence of any specific substance outside the container was detected inside the container: there are no risk for safety due to container coating.
Code prescriptions for earthquake resistance: containers provide good performance in relation to seismic actions. Specific structural models are required to understand how they works in a multiple assembly configuration with openings and junctions. The Italian building code is in line with the best international codes for the design for earthquake resistance.
Specific analyzes of existing legislation were also carried out in order to highlight possible incompatibilities between the container system and residential building. In the specific Italian context, the only norm that somehow contradicts the use of the containers is the internal net height of the buildings which is fixed at 270 cm. Since a HC has a net internal height of 269,7 cm, this difference is within the normal construction tolerances.
However, it is necessary to put in place all the strategies so that this height is not further reduced. In particular, if you work on the existing floor, adding another (perhaps radiant), you need to remove the top sheet of the container (which has no structural value for vertical loads) and overlay a structure (or another container) that closes the space of the lower container.

FROM CONTAINER ARCHITECTURE TO ARCHITECTURE WITH CONTAINERS

New degree of innovation in the Italian scenario

The innovation that the use of this constructive system can cause higher levels of safety, better health protection, a superior quality product and more environmentally friendly. The degree of innovation that can be achieved can be traced back to open innovation strategies where efficiency is sought through the effectiveness of collaborations, witnessed by the integration of the productive lines of the project partners; in radical innovation, which can give rise to new businesses resulting in employment generation and increased profitability, competitiveness and market share; it can be the engine of new values through the application of special hybridized "recycling" techniques and the monitoring and evaluation of the environmental impact of the proposal; it can generate incremental component innovation in support of an energy efficient high-performance OFFGRID solution with industrial process design with lower cost of production. This system also ensures a high level of customization: no serial buildings in the form are expected, but buildings made by prefabricated and pre-machined elements with high grade of flexibility in building-site. The proposal of a high-tech home where the technological innovation is based on the fundamental concepts of connection and network by mixing synergistically and circularly binomials such as: pro-action and consolidated knowledge; planning and production process; internal and external actors of the building process; professional skills and their strengthening in an innovative relationship system; guaranteed high performance and new construction techniques; regulatory updating and new valuation and calculation tools; innovative global energy management tools. In the smart building, a complete and multidimensional interpretation of domotics is given, which is not intended as a simplistic "aesthetic or precious" finishing but as an indispensable tool for making a real integration of the four fundamental design aspects: plant / shell / space / structure related to the design concept. Home automation, i.e. the integration of all systems, is real and present in every aspect of the building, not only in user interfaces, but in the complete management of all components, energy efficiency and static efficiency through, for example, the realization of a structural solution that disclores the underlying critical situations without on-site inspections and controls. New markets are also emerging since the project and product proposal is disseminable (for climatic zones, seismic zoning and regulatory, national and international). The system represents a incireasing proposition, the basic feature of any innovation: a proposal that can be foreshadowed by a new market entry model with a turnkey "wet-lease and / or dry-lease" offer solution through a maintenance management service (i.e. global service) that allows programmed monitoring to ensure constant performance over time. Moving in this scenario requires: a) product innovation, b) designing and implementing a system that goes beyond serial design, c) a professional action that reflects the identity of the project and context, developed with based on process and product industrialization criteria, d) construction of charts containing morpho-typological functional, plant and structural solutions and identification of answers for climatic bands, e) definitions of structural and functional strategies to assemble modules; experimental certification definition, also transferable to other similar experiences, through the

PdR13[10] review in collaboration with UNI[11]. They appear to be innovative activities in building simulation models of energy behavior, tranferable to other experiences; as well as appear innovative the construction of simulation models of structural and seismic behavior, plant design and implementation activities and self-learning digital systems for the automated management of plants and appliances for controlling production and energy consumption transferable to others experiences. In addition, we are developing instruments for monitoring energy, structural and seismic. The proposed product has a positive potential impact because it situates in the growth of the prefabricated buildings market. It is in a real estate market that has kept, compared to the crisis on high performance housing; it responds to a mandatory and regulatory framework that requires continuous improvement of certifiable and certified performance. It is a system that meets the needs of different categories of users and is part of intelligent city research, where the structures which make up the city will have to be largely derived from recovered materials, waste or the highest technological content that make a real example to rebuild an urban environment and to live in with the highest sustainability systems. It also represents a product that proposes energy management of the property with attention to the quality and ability to regenerate the natural resources of the environment and to control its ecological impact.

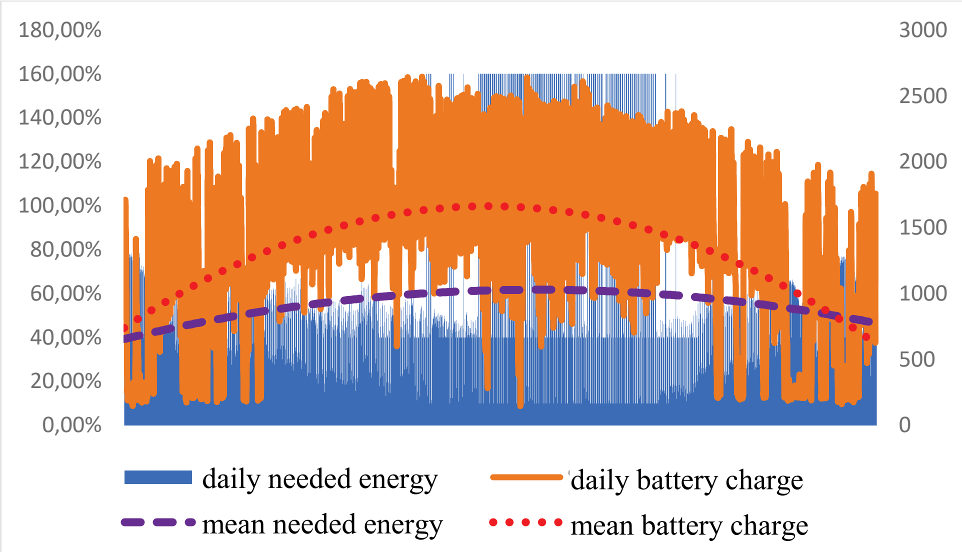
Structural seismic safety

The general philosophy is to identify the elements to be protected during seismic events in the containers; for this purpose the dissipative/ductile and sacrificial elements are identified in the connections: these elements will protect the dameging of cells by dissipating energy. This choice, in addition to simplifying the analysis, is in line with the latest regulatory developments: buildings are designed not only to safeguard the lives of people but also to limit damage and above all repair costs (high value of the AAL index - expected annual average loss). Even finishes, as far as possible, will follow the same philosophy, focusing the dameges in precise, easy access points and allowing repair as quickly and easily as possible. However, even when damages require more invasive operations, the system provides for the possibility of dismantling, repairing the connection and replacement elements of the cells that should have been kept essentially intact. In extreme situations, the intrinsic ductility of steel cells should, however, ensure the preservation of life and should only repair or replace damaged cells. In the project hypothesis the building should return usable in days, worse in weeks. All this, of course, if the foundation damages do not prevent the further use of the same: in this case, however, the building can be dismantled, repaired and reassembled in a different place, where new foundations have been installed in the meantime. The remote monitoring system allows the detection of damage points without having to resort to long and widespread investigations: the lack of damage is immediately reported, local damage is detected and, most of the time, allows for a focused intervention in the single point of damage, without putting off the building for a long time; in some cases allows to restrict the intervention area allowing other parts of the building to be used. In the multi-storey type, the dissipative/sacrificial elements, designed to prevent the cell elements from transferring forces that damage them, are located at the base and in the horizontal links of the container columns, so that they will have elastic operation inside them by concentrating dissipation and damage in connections with foundations and between columns. These connections identify the so-called "other spaces": other spaces will have a minimum size of 7.5 cm but preferably they have size to allow access to men or tools necessary for repairs/replacements of damaged items. In the irregular free aggregation typology, the horizontal connections between the containers will be sized in the elastic range, even in order to ensure the over-resistance of the cells (however, if possible, they must be damaged before then cells), the connections to the foundations (hard to access) will follow the same philosophy, and then, in the elastic field, will transfer only vertical forces: the dissipative and sacrificial elements will then be located beneath the nuts of the columns on the edges of the building so that it can be swiftly replaced.
Monitoring dissipative base elements allows you to know the stress status that involved foundations and thus allows you to indirectly evaluate if they are inctact or they need for repair. Façade panel joints will allow relative movements between the columns (oval-shaped holes) or they will focus the damage on the corner fastening and connecting brackets (turning the holes on the brackets, protecting the panel profiles obtained by using threaded inserts or the like).

[10] UNI PdR 13: 2015 Environmental Sustainability in Buildings - Operational Instruments for Assessing Sustainability.
[11] Italian Authority for Standardization.

Energy efficiency

The work for container conversion into housing is technologically convenient; however, to get to the finished product (the home) you have to undergo detailed studies to make it truly innovative for use different from the one it was intended for. we have analyzed the energy requirements in three strongly different environment contexts to verify the adaptability and feasibility of energy solutions to different environmental contexts in the Italian landscape, even in extreme cases: Milan (Po valley, 2404 degree-days), Livigno (mountain, 4648 degree-days) and Palermo (mediterranean sea, 751 degree-days). Compliance with NZEB requirements in national energy legislation impose tight constraints on both opaque and transparent envelopes and the choice of plant types, pushing for the massive use of renewable sources. In this study, we went further, thinking of building a OFFGRID system, that is completely independent by the energy point of view, exploiting renewable energies. An OFFGRID building is totally self-sufficient, not connected to any network and able to handle the normal needs of energy, gas, hot water, connectivity, etc . A reality that exchanges with the ecosystem only sun, wind and rain without consuming other resources or polluting. In an OFFGRID building electricity is produced from renewable sources in the territory where it is built such as: photovoltaic, wind, hydroelectric, geothermal, etc. The energy thus produced can be stored inside the building through the use of accumulator batteries, which return the stored electricity if more electrical requirements are required than that produced at that time by the panel. Heat can be obtained thanks to vacuum tube solar panels to increase winter production and get high summer temperatures.



Graph. 1 Qualitative diagram of the relationship between the energy required for home and the % of battery charge

This heat can be stored in a seasonal accumulation, integrated cogenerators or boilers production (running on hydrogen or plant products locally) to heat in winter the wall or floor radiant heat at low temperature. The heat produced during the summer is fed into the seasonal accumulation or it is used to supply an absorbing machine for the production of frigories (i.e. cooling). This closes the thermal cycle, heating the building in winter and cooling it in summer. Well-insulated and naturally ventilated, walls have a great impact on the energy savings required for heating and cooling the building. The meteoric waters can be accumulated in a tank suitably sized according to local climatic conditions. This cistern, with an appropriate volume, is a useful thermal pre-cooled flywheel, maintaining a temperature of about 15 degrees throughout the year. Such water can be potable (by means of filters and / or UV treatment) or demineralized. An energy project of a building requires the definition of the building-plant system as a whole organism, because the construction casing and the plants contribute synergistically to the determination of energy consumption. Just think how to improve the energy quality of the casing, for example with a careful design of thermal insulation, has an immediate reflection on energy consumption. To ensure optimum consumption and to compensate for the energy demand through renewable sources, it is essential to provide, through adequate energy diagnosis, all the elements regarding energy consumption and possible energy problems of the building-plant system, to understand which are the situations that require the greatest energy needs and whether such requirements are justified or restrictable.

A POTENTIAL: THE CONTAINER AND THE EMERGENCY HOUSING

Constructive system with containers can easily be inserted also in post-calamity emergencies, of which, unfortunately, Italy is often a victim. The design idea consists of starting a 40-foot HC container with significant stability qualities and realizing with it a totally autonomous and independent housing module from the energy point of view. What is commonly referred to as a container, and referred to by the media, refers to a constructive system for shipyard barges, not too much change, to post-calamitous homes, calling it too generically containers.

So, they are actually prefabricated dwelling modules (such as yard booths) made of constructive systems and materials designed for occasional use, without particular care to comfort, durability and performance. Instead, our intention is to use a HC40 container with internal thermal insulation and coatings, equipped with prefabricated bathroom and integrated plants, ready for water and electric plug in only. Early studies are encouraging: such a building can achieve performance from nZEB building, in line with more traditional systems. For emergency use, this system can be a convincing alternative to both prefabricated modules and wood bothy. Compared to prefabricated modules, made of metal frame and sandwich panels in phenolic or polyurethane foams, the system proposed from us is entirely dry made, with weathering steel casing, unglued thermal insulation and plasterboard interior coatings, to obtain a completely dry stratigraphic, totally removable, reusable and recyclable. Traditional prefabricated modules are easily damaged, so that many are not reusable after a single use, except after expensive repairs. This is why they are abandoned in areas that compromise the right use of the soil, as well as being a disheartening waste of resource, not last economical. Compared to the wooden modules, assembly is almost completely done in the workshop, using anigroscopic materials, durable and unattached by molds, insects or fire. The advantage can be found in the speed of laying (few minutes), of transport (normal truck) and especially in the duration of the module itself. Compared to both, the useful life of the proposed system is certainly longer and with a higher intensity: it was born as an industrial product for freight transport; it becomes, with few modifications, a home easily stored[12], which tolerates all kind of climate and structural stress; it can be used for emergency, several times, easily repaired, and quickly transported and installed. When conditions no longer allow it to be used as a home, it can be emptied / decked out of coatings and can become a temporary set-up for an outdoor café or patio; even when this function is no longer allowed[13] due to structural reasons or economic convenience, it may be disassembled and its components reused in the steel industry; as the last stage can be recycled as steel and then can start the cycle from the beginning. As a matter of fact, determination in trying to provide a valid support to a part of the emergent problem is demonstrated by what has been stated earlier. There is, in fact, a mutual will to reach a factual cooperation, analysis and field work that research institutions have always promoted and wish to provide. This is a challenge that can not be based on possibilities (whether economic or regulatory) but on the institutional will to deal in time with an ineligible state of fragility (seismic for example) of our country and to make the concept of resilience concrete and enforceable. Only in this way the forecast for smart, inclusive, sustainable growth will be achieved in the EU's 2020 ambitions.

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[12] In large cargo ships, up to 9 containers are superimposed, which also resist ocean burrs.

[13] Under normal conditions of use - exposed to atmospheric agents and oceanic saltiness - a marine container can withstand over 50 years.

Analysis on the effects of exterior openings on residential building energy consumption in Northeast U.S. climate conditions

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Abstract

Energy, and its consumption rate by human societies will continue to be an important topic globally. The built environment, and buildings in particular have much to contribute to the solution by enhancing energy efficiency. There are international efforts in the building sector to develop and implement regulations for building and construction of more efficient buildings. The International Energy Conservation Code (IECC) is one outcome of such efforts, and its multiple iterations have been adopted by many countries. The Building Energy Code Program (BECP) administrated by the U.S Department of Energy, is intended to improve the efficiency of residential and commercial buildings, and is based on the IECC regulations. The existing codes are necessary, but alone are not sufficient as has been experienced in the last two decades, to achieve the maximum potential economic and environmental benefits of energy consumption. This study aims to simulate the effects of exterior openings on the residential buildings' energy consumption through computational design and analysis. Designbuilder, a building automation and simulation software program, has been utilized for the analysis. Analyses were based on new residential construction in the Northeast region of the United States, by considering local climatic conditions. Results of this study has indicated an overall 3.42 kBtu/ft^2 of annual energy savings in a detached single family house, which represents a 11% reduction in total building energy consumption.

Keywords: Residential building; Building energy efficiency; Window to Wall Ratio

1. Introduction

Buildings are responsible for approximately 40% of global energy consumption [Ramesh et.al, 2010]. Therefore, they are also capable of saving significant amount of energy and environmental emissions if they are managed well. Methods for producing, distributing, and consuming energy has received global attention in recent years. Recently, various fields of engineering have focused more on energy consumption of their products and designs. However, buildings and the energy they consume dwarfs energy consumption by a single consumable product and thus may be considered as one of the most significant areas for potential improvement. Furthermore, improved designs have the potential to improve occupant comfort as people spend a significant amount of their time within buildings, reported to be approximately 90% for an average person in the U.S. on a daily basis.

There are international efforts in the building sector to develop and implement regulations for building and construction of more efficient buildings. The International Energy Conservation Code (IECC) is one outcome of such efforts, and its multiple iterations have been adopted by many countries. The Building

Energy Code Program (BECP) administrated by the U.S Department of Energy, is intended to improve the efficiency of residential and commercial buildings, and is based on the IECC regulations.

Energy standards for buildings and construction are not typically mandatory, but are recommended for implementation. On the other hand, energy codes are regulatory and are mandatory for buildings and construction to apply. This study has utilized both energy codes and standards in building modeling and simulations.

Human behavior also plays a significant role in controlling the energy consumption in buildings. A study by Sorgato et al. (2016) show that occupant behavior related to open window duration and ventilation control is one of the main factors affecting residential buildings' thermal performance. The study points out that technological innovations should come into action to help reduce building energy consumption while providing sufficient comfort level for occupants.

The influence of the early design decisions such as building shape and construction materials on building performance have been demonstrated [Morbitzer and Christoph, 2001; Granadeiro et al, 2013]. Murgul et al. (2015) studies the effects of solar energy on the architectural shape of the buildings, and the corresponding influence of building shape in terms of the form, orientation, window placements on energy demand. A study by Wen and Hiyama (2016) examines the impacts of the Window to Wall Ratio (WWR) for an optimal thermal and daylight in an office building. Study suggests that windows placement and orientation is a crucial factor in early design stages [Wen and Hiyama, 2016].

Building on existing techniques and technologies, this research work aims to simulate the effects of exterior openings on the residential buildings' energy consumption through computational design and analysis that would otherwise occur throughout the lifetime of the building. Designbuilder, a building automation and simulation software program, has been utilized for the analysis.

2. Methods:

A study by Aktas and Bilec (2012) has shown that the average lifetime of residential buildings in the U.S. to be approximately 60 years, and hence the value was used in the study for building lifetime. The study demonstrates the amount of energy that new construction could save by appropriately designing exterior openings on future building construction. This study has only focused on the new construction as compared to existing buildings as it is more cost efficient and easier to implement the studied techniques on new construction. All three techniques mentioned in this research could be simply checked for or required on new construction during the early design phase by architects and engineers. The following techniques have been analyzed in the study:

- Window-to-wall ratio (WWR)
- State-of-the-art window types
- Shadings

United States has been divided into different climatic zones based on weather conditions. Fig. 1.a presents the various climate regions adopted by the Building America Program. The program is sponsored by the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) [EIA, 2012]. It is based on the climatic information of the IECC and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [Baechler et al, 2010]. Building America Program provides guidelines for building practices based on climate in order to get higher energy efficiency in buildings. This study has focused on the Northeast region of United States which is in the cold/ very cold region [EIA, 2012].

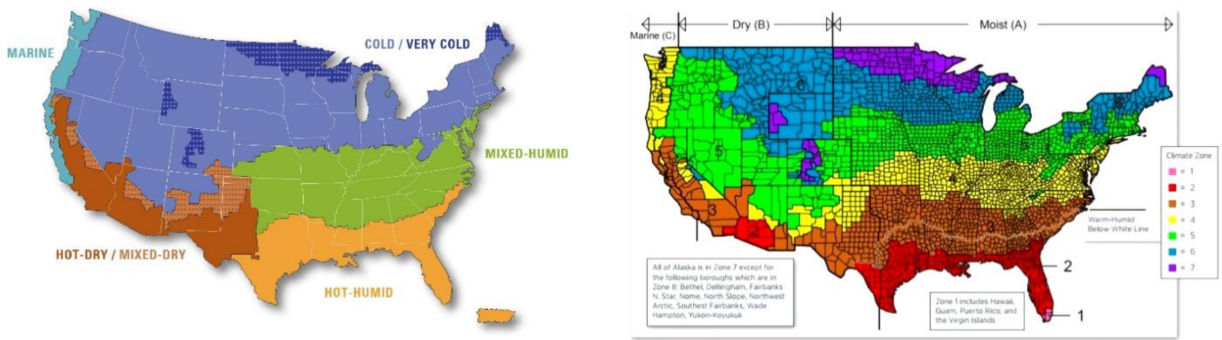

Figure 1. a) U.S. Climate Map as proposed by the Building America Program [U.S. DOE, 2011], b) International Energy Conservation Code (IECC) Climate map [Baechler et al, 2010].

Number of heating degree days (HDD) and number of cooling degree days (CDD) are frequently used for defining weather condition in a region, and they are especially important for studying energy efficiency and consumption of buildings in a particular climate [EIA, 2012]. Each region in the U.S. is assigned a climate zone based on its HDD and CDD in IECC2012. The simulation for the model building used Hartford, Connecticut as its location. Based on the U.S. climate zone map, the studied region is located in climate zones 5, 6, and 7 [IECC, 2012]. Therefore, codes related to these climate zones were utilized to design the base model.

The number of HDD and CDD provided by the IECC for the U.S. regions were compared to the information provided by the Building America Program. According to the Building America Program, the cold climate for building practices has been defined as a region with approximately 5,400 to 12,600 heating degree days [U.S. DOE]. Therefore, both climatic characteristics provided by different administrations indicated that, the whole studied region was located on the cold/very cold region in the climate map provided by the Building America Program [IECC, 2012]

Number of new residential construction in the Northeast region was taken from the U.S. Census Bureau and the U.S. Department of Housing and Urban Development [U.S. Census Bureau, 2016-17]. The states have been studied in the cold region are: ME; NH; VT; MA; RI; CT; NY; and PA.

Following the information provided in the database, number of detached, single-family residential buildings that were built annually was estimated as 44,635 [U.S. Census Bureau, 2016-17], which would imply nearly 2.3 million homes in the next 50 years if current trends remain constant. This study has assumed that the number of new construction will remain approximately at a similar rate for the next 50 years.

The developed model building was verified with actual energy consumption amounts provided by the national databases [EIA, 2009; IECC, 2012]. IECC 2012 was applied on the base model since 6 states out of 8 states studied in this research are currently using IECC 2009 or 2012 for their new construction. As a result, the outcomes from the new techniques studied in this research could be considered as additional savings on top of the latest version that is currently in effect in the region. Base model building was verified with the code requirements with the errors of 0.4% for IECC 2000 and 3.6% for IECC 2012.

3. Results and Discussion

3.1 Window to Wall Ratio

The first technique that was applied on the model building was the window-to-wall ratio (WWR). It is the proportion of the opening area to the building envelope area. Windows and openings are responsible for both heat gains and heat losses in buildings. Therefore, they are important factors in terms of heat balance control in buildings. Architects can manage and control the amount of openings and their placing on the building envelope with respect to climate requirements. WWR is responsible for saving or spending large amounts of energy through its construction, and is a basic technique that can be modified by architects and engineers in the early stages of design.

Based on climate zone characteristics chosen specifically in this study, heat gain through sunlight is considered as a desirable heating source for living spaces. The strongest sunlight in the studied location was obtained on the south side of the building. Sunlight received through north-facing façade was also deemed acceptable. According to Baker and Steemers (2014), north and south are the best sides of the buildings to place windows. East and west sides of the building do not get direct solar energy except for a few hours during the day in winter months, when sunlight is most needed. On the other hand, large WWR ratios on the east and west facades may result in unnecessary heat loss through the glazing and framing. Therefore, they are good options to be removed in order to control the overall window to wall ratio. As a result, windows in the east and west were modified to smaller sizes and some were removed altogether if deemed unnecessary. Overall, WWR for the building model was therefore decreased from 15.3% to 11.5%. The impact of transitioning the WWR is demonstrated in Fig. 2, where differences of up to 50% can be observed during winter months.

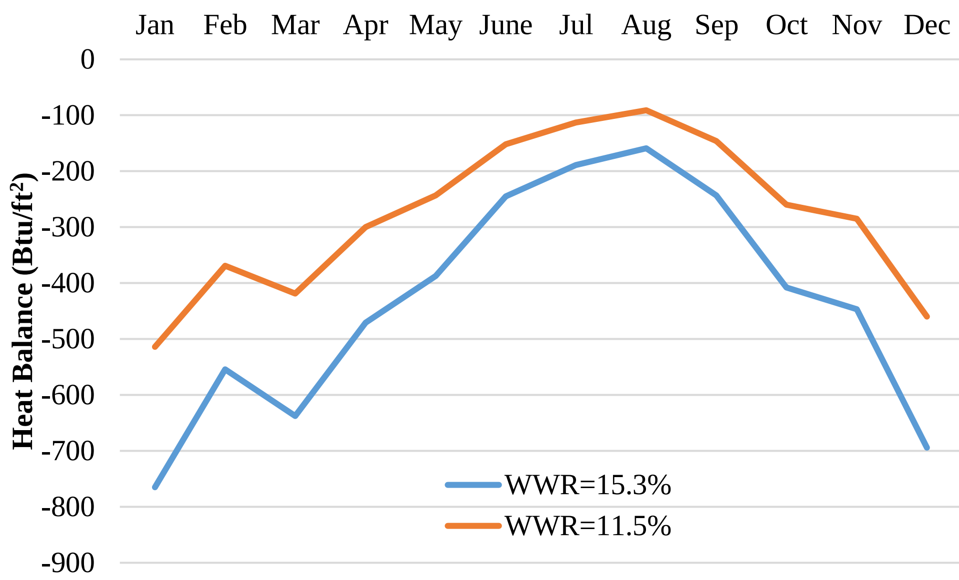

Figure 2. Fabric and Ventilation heat balance, Energy plus simulation results for WWR. 1 Jan to 31 Dec.

The results of optimizing the WWR is provided in Table 1. Amount of energy savings were 1.4 kBtu/ft^2 annually which is approximately 4.6% of total building energy consumption. Overall saving is roughly 454 trillion BTUs of energy savings over the lifetime of the new construction for the next 50 years.

Table 1. Window to Wall Ratio (WWR) and energy requirements before and after technique implementation.

	Total (%)	North (%)	East (%)	South (%)	West (%)	Energy Per Total Building Area [kBtu/ft^2]
Above Ground WWR: Before implementation	15.26	15.58	11.44	22.81	8.22	30.6
Above Ground WWR: After implementation	11.54	14.37	4.67	21.83	4.94	29.2

3.2 Window Type

Glazing in the building exterior envelope causes a large amount of heat loss during winter months in cold climates. Therefore, glazing type becomes an important factor for efficient building design and construction. Glazing heat transfer characteristics are defined by the U-factor. Thermal transmittance (U-factor) is the rate of the heat transfer in a square meter of the material divided by the temperature difference across the material. The less the U-factor is, the higher resistance the window has to heat loss. U-factor and energy demand required by IECC 2012 is presented in Table 2 together with values offered by triple pane windows, which is the current state-of-the-art in high efficiency glazing options.

Table 2. Effects of the glazing type on energy demands before and after technique implementation.

	U – factor [Btu/h-ft2-F]	Energy Demand [kBtu/ft^2]
IECC 2012	0.32	29.22
Triple pane window	0.14	27.22

A U-factor of 0.32 Btu/h-ft^2-F was already required by the international energy regulations. In this study specifically, triple pane windows were analyzed. The new U-factor was 0.14 Btu/h-ft^2-F for the new window types. The goal was to understand the amount of energy savings through more efficient glazing. Results are presented in Fig. 3, where a significant decline in energy demand can be observed with a switch from a U-value of 0.34 to a U-value of 0.14. As a result, the amount of the energy savings through the triple pane windows were 2.0 kBtu/ft^2 annually, which corresponds to 639 trillion BTUs over the next 50 years of new construction. According to Fig. 3, heat loss through glazing has been decreased by 77%. Similarly, zone sensible heating which is provided by the HVAC systems, has been decreased by 18%. Overall, a 6.5% reduction in energy consumption was obtained through the efficient glazing.

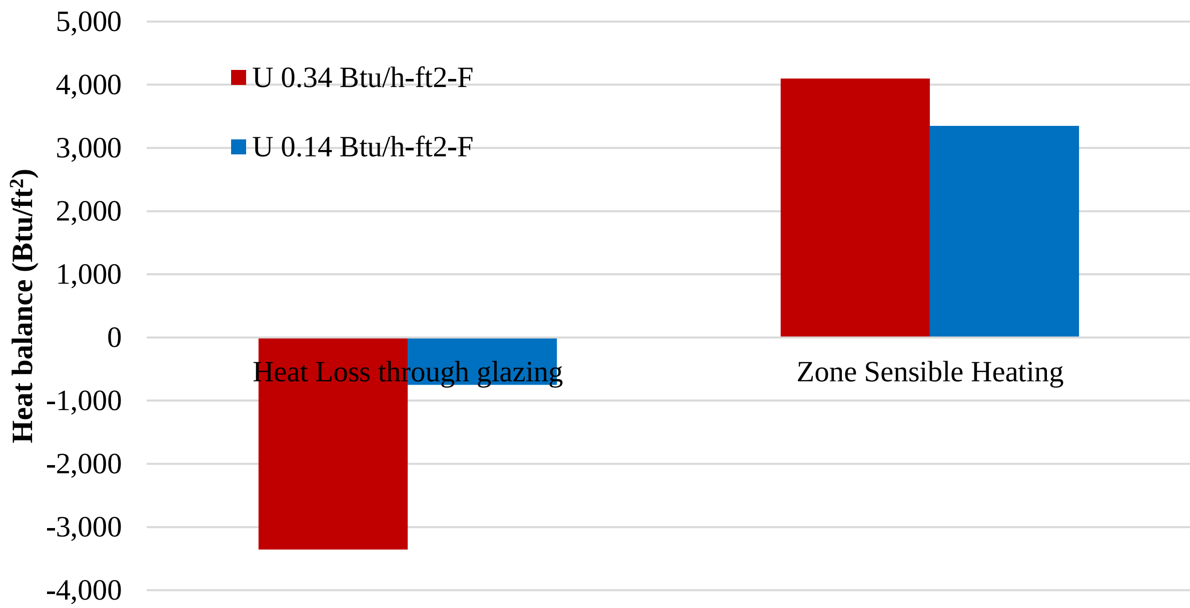

Figure 3. Fabric and Ventilation heat balance, Energy plus simulation results for glazing. Effects of the window type on heat balance, 1 Jan to 31 Dec.

3.3 Shadings

The basic purpose of shading devices is to prevent solar radiation from reaching the building interior during hot seasons [Kim et al, 2012]. Appropriate shadings should be installed on the windows to control the solar heating energy in the buildings. Shading devices could be positioned inside of the window, outside of the window, or in the middle of two panes of the window. Overhangs, Louvre, and side fins are some examples for exterior shadings which were assessed in the study, and are illustrated in Fig. 4.

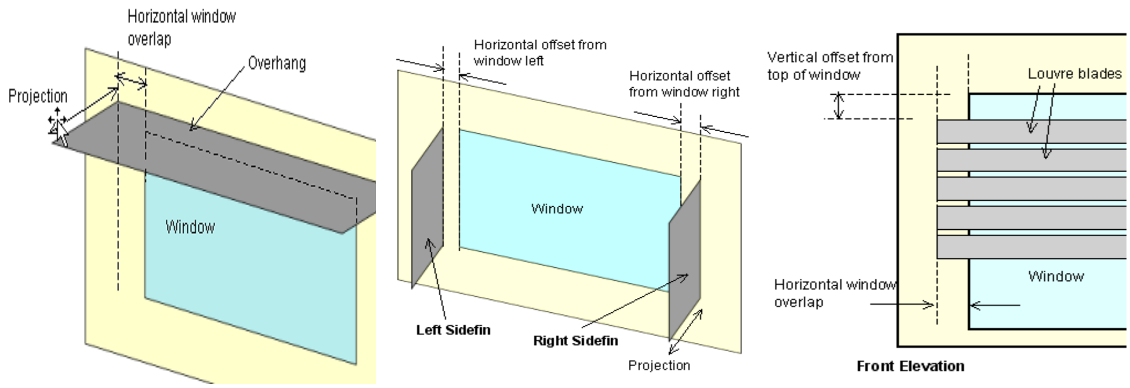

Figure 4. Shading types a) Overhangs b) Side fins c) Louvres.

Initially, no shadings were used for triple-pane glazing. The building energy demand was calculated as 27.2 kBtu/ft^2 annually. Following that, various shading devices were installed on the model building to understand the effects of each shading type on the building energy consumption. Interior shadings were turned on for triple-pane windows. Simulation results showed a higher energy demand comparing to the building model with windows without shadings (28.0 kBtu/ft^2-yr). Louvre shadings and Overhangs were utilized for outside and same interior shadings were used for inside. The results showed a total energy demand of 28.0 and 28.1 kBtu/ft^2-yr respectively, which were still higher than the windows with no shadings. Next, the baseline model was modified by considering a schedule for shadings for interior shadings and local shadings with respect to shading demands in summer, and overhangs were used instead of Louvre shading types. However, results were still higher than the first iteration with no shadings for windows.

Based on the results of this analysis that are presented in Fig. 5, shadings did not show a favorable outcome in energy savings in Connecticut due to a dominant cold climate in the region. The cold climate of the region and thus heating demands were more dominant than cooling demands in the model building. Therefore, it is better to receive more sunlight reaching into the buildings. As a result, shadings, if placed, should have the ability to be turned off during daytime in winter months. However, shadings with smart control systems could be suitable for residential buildings, but further studies are required about the effects of shadings in new construction in cold climates.

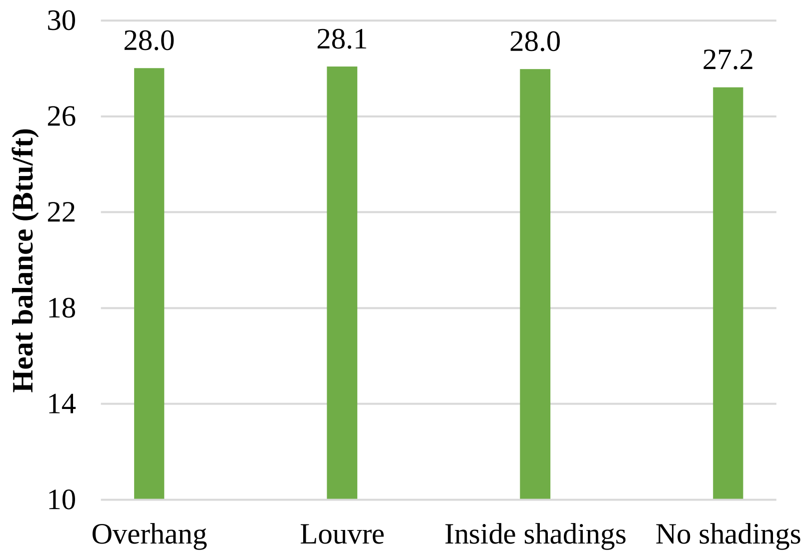

Figure 5. Heat balance for various shading types.

3.4 Cumulative results

This section provides a comparison between the base model and the final building model with evaluated techniques applied to the model. The final goal is to understand the differences between the amount of the energy consumption in the base model which had been designed and verified by the IECC 2012 regulations, with the proposed building model after implementing existing passive techniques.

Table 3. Cumulative results for energy savings by each technique, analyzed separately

Technique	Energy savings per residential building, [kBtu/ft^2-yr]	Energy savings compared to baseline model, %	Total energy savings in new construction over its lifetime [trillion Btu]
Window to Wall Ratio	1.4	4.6%	435
Window Type	2.0	6.5%	639
Shadings	-0.8	-2.5%	-243
total	3.4	11.1%	1,074

4. Conclusions

This study has focused on building exterior openings and available passive techniques that could be implemented to improve efficiency for new residential construction in cold climates. Based on the goals of the study, window to wall ratio, window types, and shadings have been analyzed through simulating their effects on a model home based on an average home in Northeast U.S., and verified with the 2012 IECC code.

Existing techniques analyzed in this study indicate potential energy savings in the cold region of the Northeast U.S. by controlling building openings. Based on the results of this analysis, shadings did not show a favorable outcome in energy savings in Connecticut due to a dominant cold climate in the region. Overall, an additional 11.1% of energy consumed by single family detached houses could be saved by managing the WWR and employing efficient window types, beyond the requirements of the 2012 IECC code. In summary, future detached single family houses are capable to save 320.4 TWh (1,074 trillion Btu) of energy through new construction in the next 50 years if they implement the analyzed techniques in this study.

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4th Residential Building Design & Construction Conference

Thermal-dynamic performance of collective buildings using low temperature for heating systems. Northern Spain application

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Abstract

The use of low temperature heating systems is much more energy efficient, because the heat source could be at least in part water from solar heating and the heat emitters for low temperature water are mainly based on low temperature radiators or radiant floors. This research compares the dynamic behavior of these heat emitters during the most extreme week of the year for a collective housing with very low energy consumption according to European Building Codes.

The thermal stability and energy consumption are analyzed for both (radiators and radiant floor). The heating starts close to moments of maximum heat demand, which deals with the requirement of maintaining constant temperatures during day and night. The study is applied to an oceanic climate zone in a coast city in northern of Spain. The need of adapting the heating demand to the energy supply has led to a study about the influence of the size of the thermal energy storage tanks.

The results show that the radiant floor reach higher and more stable temperature levels in the indoor air. With the proposed radiant floor and the thermal design of the building the indoor air temperature difference between day and night is on average 0.32ºC while this difference is 0.69ºC for radiators. The radiant floor operates with lower water temperature in the heating system than the radiators and more close to the indoor air. This fact also allows approximately a double heat storage capacity of the water tank for the radiant floor, providing more energy displacement between the supply and the heating demand periods, which reach nearly 50%, and making it very suitable to be powered with renewable energy sources such solar thermal energy.

Nomenclature

ΔT	Temperature difference (ºC)	$\dot{m}$	Mass flow (kg/s)
c_p	Specific heat (kJ/kgºC)	P	Power (kW)
d_x	Pipe spacing (mm)	ρ	Density (kg/m^3)
δ	Pipe diameter (mm)	T	Temperature (ºC)
E	Energy (kWh)	Th	Thickness (mm)
k	Thermal conductivity (W/mºC)		

Subscript

air	Indoor air	*n*	Night
ap	Apartment	*o*	Outlet
d	Day	*RHF*	Radiant heating floor
H	High limit	*RTUs*	Radiator thermal units
i	Inlet	*set*	Setpoint
ini	Initial	*te*	Thermal emitters
L	Low limit	*w*	Water
mCHP	Micro combined heat and power	*zone*	Zone of the building

1. Introduction

The increase in energy efficiency in combination with the use of energy from renewable energy sources constitutes essential efforts to reduce primary energy consumption to sustainable levels and decrease greenhouse gases emissions (Annex 54 IEA 2014).

Radiant floor heating systems have been used for a long time (Shoemaker 1954). The great potential of radiant systems comes from the possibility of coupling them with renewable energy sources or systems that allow high efficiency and energy savings due to the low difference that is required between the temperature of the water circulating through the pipes and the indoor air heated (Olesen 2000). This advantage also causes an improvement in thermal comfort by producing a uniform distribution in ambient temperature in the room with a difference between the maximum and minimum temperature of the floor which must be as low as possible (Shin 2015).

The most promising power systems to supply these low water temperature systems combined with thermal storage such as water tanks or phase change materials (Zalba 2003) are heat pumps (Cabrol 2012) for off-peak management, micro combined heat and power, mCHP (Nuytten 2013), and solar thermal energy systems (Huang 2014).

The present paper analyzes the dynamic behavior of a heating system powered by a mCHP and equipped either with a radiant heating floor (RHF) or with low temperature radiators (RTUs).

2. Installation and building models and calculation

The heating system studied in this work is applied to a residential collective building located in Gijón (oceanic climate), in northern Spain (González Prieto 2015), for which 24 apartments over 3 levels (first, intermediate and upper floors) and ground have been simulated. Each of the floors consists of 10 areas: 8 apartments and 2 common areas. For the 1st floor: 1A, 1B, 1C, 1D, 1E, 1F, 1G y 1H, Z11 y Z12. The layout of the 1st floor is shown in Fig. 1 and the geometry is the same for all the floors. The usable area considered per level is 455.55 m^2. The facades are oriented 45º South-East and Northeast with a 3 m height between floors. The geographical coordinates of the location are 43º 32´ 43´´ North, 5º 39´ 43´´ West.

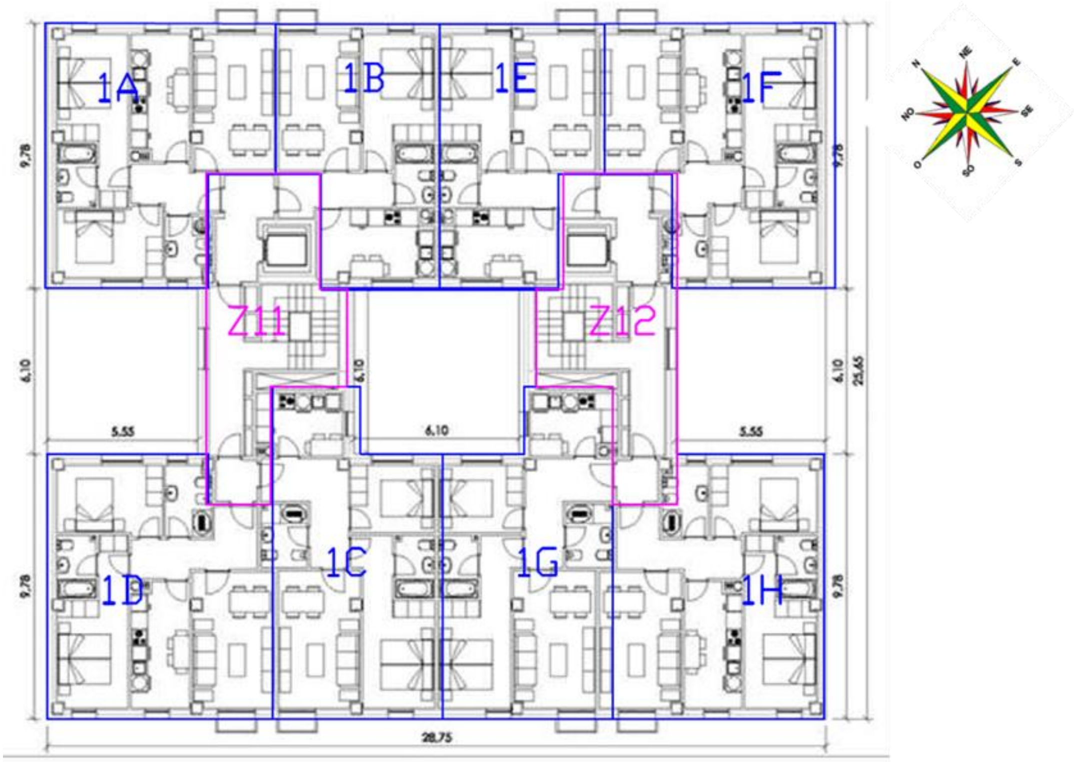

Figure 1. Layout of the apartments in the building.

The design of the building envelope and the thermal systems, which also include heat recovery from the ventilation circuit, follow the requirements suggested by Spanish law under the CTE 2007 standard (CTE 2007), obtaining "A" qualification for maximum energy efficiency. The thermal energy demand of this building, calculated with a setpoint temperature of 20°C, is 14.1 kWh/ (m^2year).

This work focuses on the coldest week of January, the second week of the month, from 168 hours to 336 hours from the beginning of the year. The setpoint temperatures of the apartments are 20ºC from 8:00 a.m. to 23 a.m. and 17ºC overnight, from 23 p.m. to 8 a.m. The thermal load demand is shown in Fig. 2 and can be appreciated that there are peak loads every day at 8:00 a.m. when the setpoint temperature changes from 17 to 20ºC and the heating power system is turned on, with powers, that depend on the day of the week, ranging from 22 to 30 kW. The requires power decreases during the day to a minimum between 0 and 5 kW, to increase again to values between 5 and 12 kW at 23 a.m., when the setpoint temperature changes from 20 to 17ºC and the heating system is turned off.

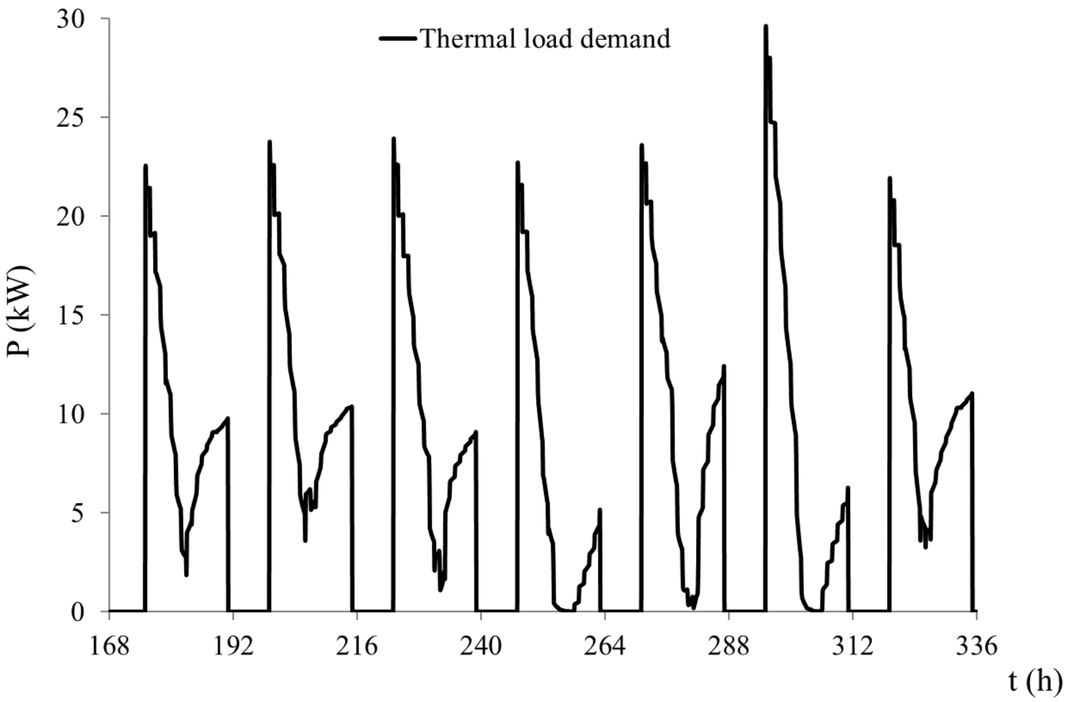

Figure 2. Thermal load demand during the coldest week of January under operation mode studied.

The heating system shown in Fig. 3 comprises a microgeneration unit, mCHP, which includes an internal combustion engine, a plate heat exchanger and an electric generator; a storage tank, which connects the primary and secondary circuits; and thermal emitters, which may be a radiant floor (RHF) or radiators (RTUs) depending on the case studied a) or b). The Fig. 3 also shows nomenclature concerning the temperatures and mass flows rates in each of the water lines; $T_{mCHP,i}$ and $T_{mCHP,o}$ are the inlet and outlet water temperatures of the mCHP, $T_{te,i}$ and $T_{te,o}$, the inlet and outlet of water temperatures at the thermal emitters circuits of the heating system.

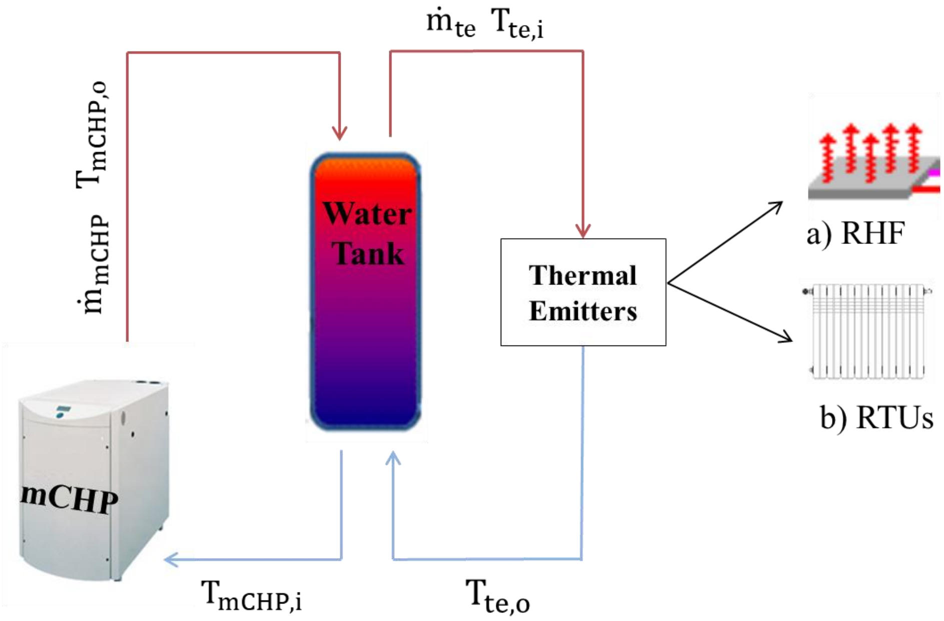

Figure 3. Schematic of the heating system; a) RHF and b) RTUs.

The operation mode of the installation is as follows. During the night, the heating system is off and the mass flow rate supplied in the secondary circuit to the thermal emitters is zero. The mCHP supplies the water tank at its maximum power until the water tank temperature reaches 45ºC, maintaining this temperature in the water tank until the morning whenever possible. In the morning, at 8:00 a.m., the control system turns on the heating system because the indoor air temperature falls below 20ºC during the night. The heating system starts sending water from the water tank to the emitters. The mCHP always works at maximum power with the restriction of not to exceed 45ºC at its output ($T_{mCHP,o}$ <45ºC), in which case, it diminish the power. During the day, the control system turns the mCHP OFF or ON and depending on the indoor air temperature of the apartment.

The control system used is based on a differential controller (TRNSYS 17 Volume 4), Type 2b by trnsys. This controller generates a control function γ_o which can take values 0 and 1. The value of γ_o is chosen as a function of the difference between two temperature limits, T_H and T_L, compared with the dead band temperature differences, ΔT_H y ΔT_L. The new value of γ_o is dependent on whether γ_{ini} is 0 or 1 as follows:

- If the controller was previously ON ($\gamma_{ini} = 1$): if $\Delta T_L \leq (T_H - T_L)$, then $\gamma_o = 1$; and if $\Delta T_L > (T_H - T_L)$, then $\gamma_o = 0$.
- If the controller was previously OFF ($\gamma_{ini} = 0$): if $\Delta T_H \leq (T_H - T_L)$, then $\gamma_o = 1$; and if $\Delta T_H > (T_H - T_L)$, then $\gamma_o = 0$.

The controller is used with γ_o or connected to γ_{ini} giving the hysteresis effect.

The heating control system, based on this controller has been adjusted as follows. The control functions γ_o and γ_{ini} are connected, setting $T_H=T_{set}$, $T_L=T_{air,3D}$ and $\Delta T_L=\Delta T_H=3$ºC. For simplicity, it has been decided to control the temperature of apartment D of upper floor, having a single controller for the entire installation. This apartment is used because it is the one with the highest thermal demand (the coldest in the building).

The maximum power of the mCHP unit is 16 kW, and its behavior is modeled in Matlab with Type 155 of trnsys by means of the balance that expresses the thermal power in Eq 1. The water tank is modeled with Type 60c of trnsys, different water tank volumes are simulated: 1000, 2000, 3000 and 4000 liters.

$$P_{mCHP} = \dot{m}_{mCHP} c_p \left(T_{mCHP,o} - T_{mCHP,i}\right) \qquad \text{Eq.1}$$

The thermal behavior of the radiators (RTUs) is given by the manufacturer, JAGA trademark BMZW, and is modeled in Matlab with Type 155 of trnsys. The operating temperature of the RTUs ranges between 45 and 25ºC. Nominal powers are chosen based on the thermal loads per floor, resulting in a configuration of one type in each floor with 2 radiators per apartment.

The heat transfer power transmitted by the radiators in each apartment of the building, which is expressed in Eq.2, $P_{RTUs,zone}$, depends on the inlet and outlet temperatures, $T_{RTUs,ap,i}$ and $T_{RTUs,ap,o}$. With these data, keeping fixed the difference $\Delta T_{RTU}= T_{RTUs,AP,i}-T_{RTUs,ap,o}=10$ºC, and given the inlet temperature, $T_{RTUs,ap,i}=T_{te,i}$, the mass flow rate is obtained for each apartment.

$$P_{RTUs,zone} = f\left(T_{RTUs,zone,i}, T_{RTUs,zone,o}\right) \qquad \text{Eq.2}$$

Fig. 4 shows the scheme and the parameters used for the proposed radiant floor (RHF); with polyethylene pipes of 20 mm diameter, 1.6 mm thickness and spacing 150 mm. In this figure, not all the floor structure is presented, only the active layer under 45 mm of a mortar layer.

Table 1 presents the data of the structure of the floor, ordered from the heated apartment to the adjacent, with the materials used, thicknesses and thermal properties of the materials according to CTE (CTE 2007). The layer of cement mortar is divided into 2 sublayers as shown in Fig. 4, 10 mm corresponding to the active layer where the tubes are inserted, and a layer of 45 mm above the active layer.

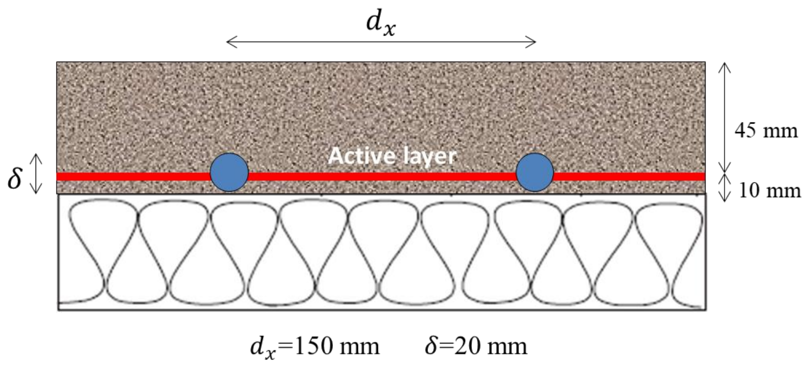

Figure 4. Radiant floor structure (RHF).

The modeling of the radiant heating floor is done by adding active layers to integrate thermally activated building elements (Romaní 2016) in the Type 56 of the building model in TRNBuild (TRNSYS 17 Volume 5).

Table 1. Floor structure layers thickness and thermal properties

Floor Layers	Th (mm)	k (W/m^2·ºC)	ρ (kg/m^3)	c_p (J/kg·ºC)
Ceramic stoneware	20	2.600	2700	1000
Cement mortar	45 10	0.625	1700	1000
Insulation (xps)	100	0.036	29	800
Concrete base	250	2.100	2200	1000

In Fig. 5 the general structure of the two heating system models developed in trnsys simulation studio is presented; a) RHF and b) RTUs. The figure shows the main elements and their connections. These elements are; the Type 56 used for the apartments model, the Type60c for the tank model, and the Type155 for model in Matlab the mCHP. Type 155 also is used for the model of the RTUs circuits (Fig.5b). Other elements are: Type15-6 for weather data, the Schedule and the macros; DIF_CONTROL (control system model), REC (recovery system model) and RESULTS (results manage). By means of the Supply calculator, the ON-OFF signal of the heating system is managed, circulating water to the secondary circuit according to this control signal. The RHF case (Fig. 5a) also incorporates the Return macro that models the radiant floor return circuit. The connections in Fig.5 are represented according to different colors in line types. The red line indicates for both the primary and secondary circuits the supply water of the heating system. In the same way, the blue line indicates connections of the return water. The green line represents connections of the heat recovery circuit, and gold line the connection of climatic variables with the building. In gray line are indicated the connections with control variables. Finally, in addition to the connections between the elements, there are connections with the macro RESULTS, in which the variables are reported. These connections are represented in black dashed line.

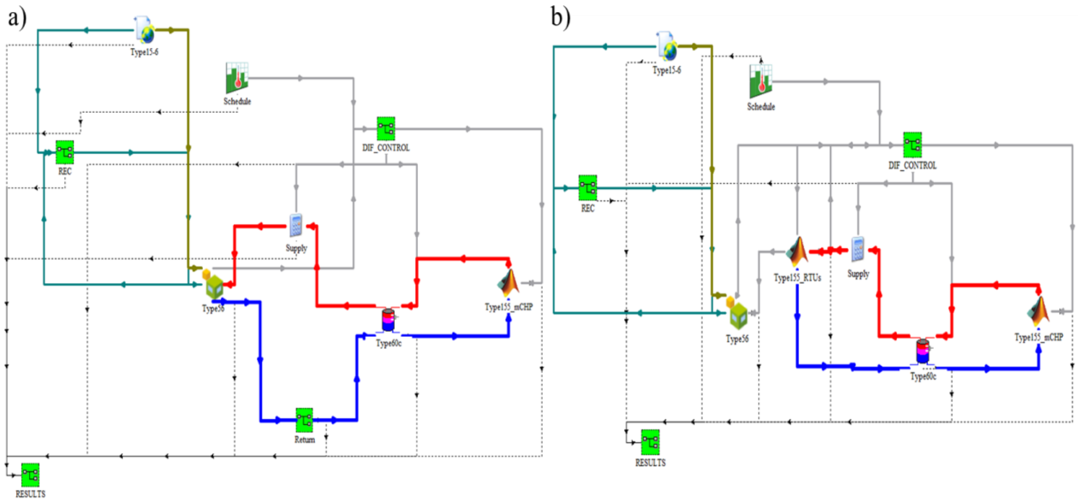

Figure 5. TRNSYS models of the heating system for: a) RHF and b) RTUs.

3. Results and discussion

The heating systems for the two types of emitter (RHF and RTUs) are simulated for tank volumes of 1000, 2000, 3000 and 4000 liters. All cases are initialized at 17°C, three days before the start of the period analyzed to avoid initial thermal mass effects. The time step used is 0.1 h.

In Fig. 6 temperature results are presented for the water tank volume of 2000 liters. In ordinates, on the left axis of the figure, are represented temperatures: outdoor air, setpoint, and indoor air for the apartments averaged by floors. In ordinates, on the right axis of the figure the average temperature of the water of the tank is represented.

In Fig. 6 it can be observed that in both cases the average temperature in the 3rd floor is lower than in the 2nd, and the last is lower than in the 1st for the whole week. The temperatures reached for RHF, Fig. 6a, are higher than for RTUs, Fig. 6b, showing also greater thermal stability. Besides, for RTUs the temperature decrease during the night is greater. Concerning the average water tank temperature, the lower limit for RTUs is limited because of the RTUs' restrictions at its inlet where the temperature cannot be lower than 35ºC. Therefore, water tank temperature does not fall below 35ºC. Nevertheless, for RHF, the inlet temperature is not restricted by operating conditions, and the average water tank temperature falls to about 25ºC. This causes greater night water tank variations for RHF, and that the average water tank temperature may not even reach 45ºC if the tank volume increases too much.

In Fig. 7 the average water tank temperature is plotted as function of the time and the tank volume. The figure shows the seven water tank charges and discharges of the week, for each the average water tank temperature rises and falls from the low to the high limit and vice versa. For RHF, it is observed how, during the charges as the water tank volume increases, the charging period lasts more, even not reaching 45ºC some days of the week for 4000 liters water tank volume. The charging periods times, averaged during the week, vary between 1.5 and 5.5 hours as the water tank volume increases between 1000 and 4000 liters. With respect to the final temperature of the water tank in the discharges, the low limit, varies according to the day of the week and the volume of the tank. The averaged water tank temperature varies between approximately 25 and 28ºC. Weekly averaged discharge periods times vary between 1.2 and 4.6 hours as the tank volume increases between 1000 and 4000 liters.

For RTUs, it is observed that for all the charges at the end the averaged water tank temperature reaches 45ºC, and that the weekly averaged charging period times vary between 0.7 and 2.9 hours as the tank volume increases from 1000 to 4000 liters. In this case, Fig. 7b, all the discharges end with an averaged water tank temperature of 35°C, except for the days 4th and 6th of the week for the tank volume of 4000 liters. Weekly averaged discharge periods times vary between 1.8 and 7 hours as the tank volume increases between 1000 and 4000 liters.

Table 2 presents the average temperatures. The indoor air temperature averaged in all the apartments of the building throughout the week (including days and nights), T_{air}, and only during the days, $T_{air,d}$, and nights, $T_{air,n}$. The water temperature at the inlet, $T_{te,i}$, and at the outlet, $T_{te,o}$, of the thermal emitters circuit. The air temperatures in the building; T_{air}, $T_{air,d}$ and $T_{air,n}$, are close to 20ºC, and they are always higher for RHF with independence of the volume of the water tank. By averaging the indoor air temperature values for each volume of the water tanks the temperature for RHF is 0.33ºC higher than for RTUs. With respect to the difference in indoor air temperatures between day and night, $T_{air,d}$ -$T_{air,n}$, averaged with the values obtained for each tank volume, is a 46% higher for RTUs. These differences, which increase slightly as the water tank volume increases, vary from 0.25 to 0.37ºC for RHF and from 0.65 to 0.71ºC for RTUs.

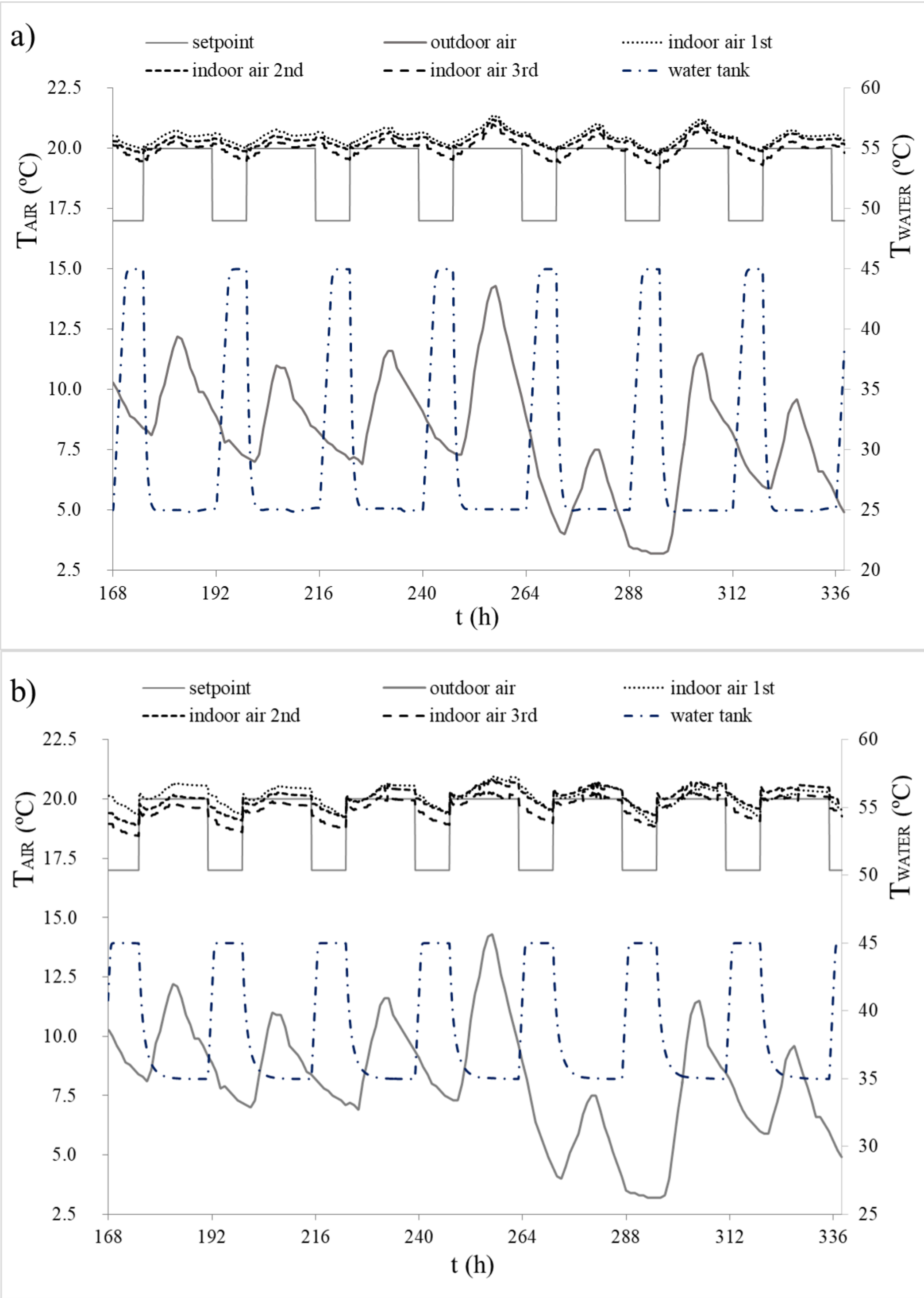

Figure 6. Temperatures of the water tank, indoor air per floor, setpoint and outdoor air during the week analyzed for: a) RHF and b) RTUs.

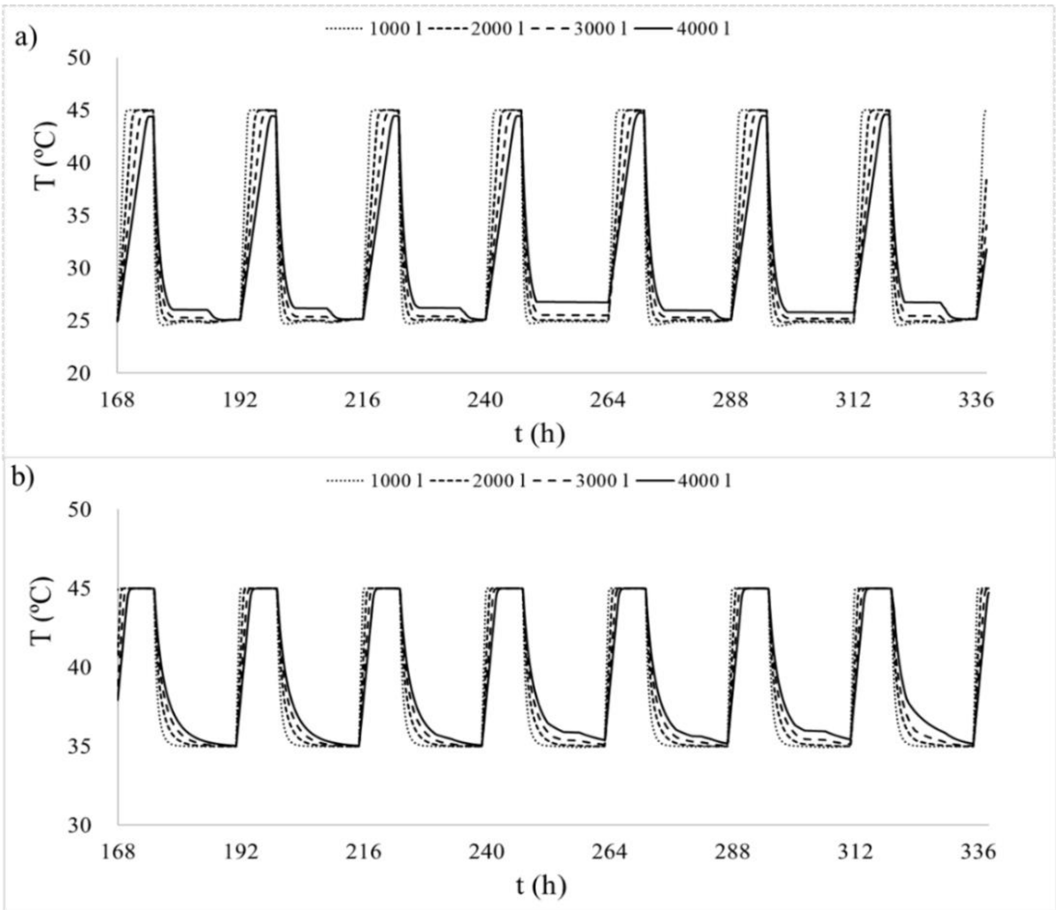

Figure 7. Average water tank temperature as a function of tank volume during the analyzed week for: a) RHF and b) RTUs.

Considering these data, it is concluded that the temperatures reached with radiant heating floor are slightly higher than with radiators and with greater thermal stability, which was already observed graphically in Fig. 6 for the 2000 liters water tank volume.

Regarding the average water temperatures at the inlet, $T_{te,i}$, and at the outlet, $T_{te,o}$, of the thermal emitters circuit, both temperatures are higher in the RTUs case for any water tank volume. The inlet temperature into the thermal emitters circuit for RHF varies from 25.22 to 27.93ºC between 1000 and 4000 liters of water tank volume, whereas for RTUs it varies from 35.43 to 36.89ºC. The output temperature of the thermal emitters circuit varies for RHF from 20.86 to 21.08ºC, whereas in RTUs cases it varies from 25.43 to 26.89ºC in the water tank volume range. The water temperature difference between the inlet and the outlet is always 10ºC by control for RTUs, whilst this difference varies from 4.36 to 6.85ºC for RHF depending on the water tank volume. This is due to the control mode chosen for each case of thermal emitter. The RHF case operates with constant mass flow rate, and the RTUs case operates with constant ΔT_{RTUs} (10ºC).

Table 2. Weekly averaged temperatures

Tank Volume (l)	Heating System	T_{air} (ºC)	$T_{air, d}$ (ºC)	$T_{air, n}$ (ºC)	$T_{te,i}$ (ºC)	$T_{te,o}$ (ºC)
1000	RHF	20.21	20.28	20.03	25.22	20.86
	RTUs	19.85	20.06	19.41	35.43	25.43
2000	RHF	20.28	20.37	20.07	26.03	20.99
	RTUs	19.94	20.16	19.48	35.88	25.88
3000	RHF	20.34	20.44	20.10	27.07	21.08
	RTUs	20.01	20.24	19.53	36.38	26.38
4000	RHF	20.37	20.49	20.12	27.93	21.08
	RTUs	20.07	20.30	19.59	36.89	26.89

These temperature data for the heating system mean that the radiant heating floor (RHF) system operates at very close temperatures to the indoor environment, resulting in a very low temperature operation with average water-indoor air differences of 2-5ºC, whilst the heating system with the radiators (RTUs) works with water-indoor air differences of 10-12ºC. Notice that increasing the volume of the tank is what makes this difference to increase.

Table 3 presents the weekly thermal energies. The thermal energy supplied by the mCHP throughout the week (including days and nights), E_{mCHP}, and only during the days, $E_{mCHP,d}$, and nights, $E_{mCHP,n}$. The thermal energy transferred by the water to the thermal emitters, E_w, and the energy transferred by thermal emitters to the indoor air only during the days, $E_{te,d}$, and nights, $E_{te,n}$. Theoretically, the sum of the total thermal energy supplied by the mCHP must be equal to the thermal energy transferred by the water to the thermal emitters, and equal to the total energy transferred by thermal emitters to the indoor air; $E_{mCHP} = E_{water} = E_{te,d} + E_{te,n}$. Nevertheless, the numerical results show energy imbalances between these three elements of the system, which, in any case, never exceed ± 5%.

The thermal energy supplied by the mCHP shown in Table 3, E_{mCHP}, is similar in the RHF and RTUs cases for a given volume of the water tank. In both cases it increases when the water tank volume increases. For RHF it varies from 1283.16 to 1351.06 kWh, whereas for RTUs it done from 1291.33 to 1366.06 kWh. These data mean increases in the energy consumption with the water tank volume of 5.3% for RHF and of 5.8% for RTUs. The thermal energy supplied by the mCHP is also divided in energy supply during days, $E_{mCHP,d}$ and nights, $E_{mCHP,n}$. Logically, in any case (RHF or RTUs), higher water tank volume causes higher mCHP thermal energy supply during the night time water tank charges. In the range of water tank volumes studied, this night time mCHP supply varies from 188.79 to 661.33 kWh for RHF, whereas it varies from 86.46 to 358.32 kWh for RTUs. Considering that the total thermal energy supplied by the mCHP does not vary too much with the water tank volume nor with the kind of thermal emitters, these data mean that of the total energy supplied by the mCHP, a greater percentage is supplied overnight for RHF.

Table 3. Weekly thermal energies

Tank Volume (l)	Heating System	E_{mCHP} (kWh)	E_w (kWh)	$E_{mCHP,d}$ (kWh)	$E_{mCHP,n}$ (kWh)	$E_{te,d}$ (kWh)	$E_{te,n}$ (kWh)
1000	RHF	1283.16	1254.72	1094.37	188.79	1033.47	304.61
	RTUs	1291.33	1284.22	1204.87	86.46	1284.22	0.00
2000	RF	1317.74	1279.65	957.30	360.44	985.23	274.97
	RTUs	1329.93	1309.84	1150.38	179.55	1309.84	0.00
3000	RHF	1334.02	1295.34	813.69	520.33	1012.84	246.53
	RTUs	1352.53	1318.27	1080.05	272.48	1318.27	0.00
4000	RHF	1351.06	1306.98	689.73	661.33	1149.67	259.78
	RTUs	1366.06	1320.79	1007.74	358.32	1320.79	0.00

Fig. 8 shows the overnight mCHP supply percentages, $100\times E_{mCHP,n}/E_{mCHP}$, by means of a bar chart according to the water tank volume and grouped according to the kind of thermal emitters (RTUs and RHF). For any volume of the water tank, it is observed that the percentage of overnight mCHP supply for RHF is always higher than for RTUs. In the RHF cases, this percentage varies between 14.71 and 48.95% depending on the volume of the water tank, whereas in the RTUs cases it varies between 6.70 and 26.23%.

The last two columns of Table 3 show the thermal energy transmitted by the emitters during day and night periods of the week. For RTUs all the heat is transmitted by the water instantaneously by the radiators to the indoor air of the apartments, so all the thermal energy transferred to the indoor air is transferred during day periods. In contrast, for RHF, the radiant floor stores part of the heat transmitted by the water during the day in the floor structure, transmitting during the night this stored heat to the indoor air of the apartments. The percentage of thermal energy transferred overnight for RHF varies slightly depending on the water tank volume, from 23% with 1000 liters, to 18% with 4000 liters.

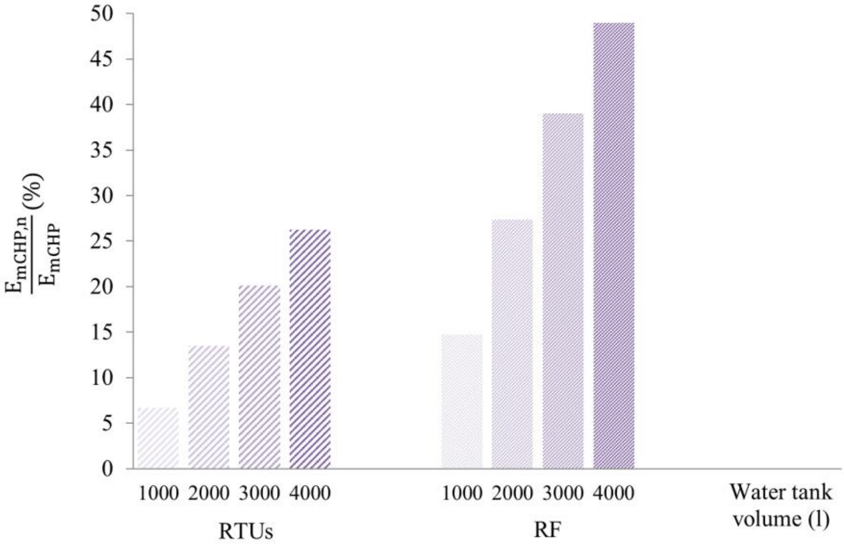

Figure 8. Overnight mCHP supply percentages

4. Conclusions

This paper compares the dynamic behavior of a heating system equipped with radiators or radiant floor varying the water tank volume, in which thermal energy is stored during the nights and discharged during the days to supply the thermal load demand peaks.

The temperatures reached in the indoor air of the apartments equipped with the radiant floor heating system are 0.33ºC higher than with the radiators. Also greater thermal stability is reached with radiant floor: the differences of the averaged indoor air temperatures (day and night periods) are 46% higher for the radiators heating system. The radiant floor operates at much lower water temperatures and closer to the indoor air temperature being the temperature difference, water temperature in the emitters and indoor air, of 2-5ºC for the radiant floor and 10-12ºC for the radiators.

There are no significant differences in the mCHP energy consumption for both systems of emitters, around 1.3 MWh. Nevertheless, when the water tank volume increases from 1000 to 4000 liters the energy consumption varies 5-6%.

The heat storage capacity of the water tank for the radiant floor is approximately the double than for radiators. With the highest tank volume, 4000 liters, and radiant floor, the overnight mCHP supply reach to the 48.95% of the energy demand, while it only reaches to the 26.23% for the radiators. This performance makes the radiant floor very suitable to attend peaks of demand and for using solar thermal energy with very high efficiency.

Acknowledgements

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Analysis Method for Resilient Design of Sheathing Panels in Residential Buildings

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ABSTRACT

Roof sheathing failure during a windstorm is a major source of damage and loss of functionality in residential buildings. This paper presents an analytical method that can be used to design residential buildings with wood panel roof sheathing that are resilient during windstorms. In the proposed method, wind loads on a building are calculated using data from experimental tests of small-scale building models subjected to wind and wind-driven rain in an aerodynamic boundary layer wind tunnel. The temporal and spatial variation in wind pressure and water intrusion is accounted for and correlated to the vulnerability of sheathing failure. The resulting fragility curve is then integrated with the windstorm hazard curve, based on the updated ASCE 7-16 wind speed maps. The integration of fragility and hazard allows the risk of sheathing failure and consequent water damage to be predicted for a given building and location. The proposed method is illustrated for an archetypical 62.5-ft by 40-ft residential building in an inland location (Omaha, Nebraska) and in a coastal location (Miami, Florida). The analyses predicted that during a typical 50-year lifetime, the building located in Omaha could expect less than 50 gallons of water infiltration, whereas the building located in Miami could expect nearly 700 gallons of water infiltration. The results can then be used to design the roof sheathing panels to meet performance objectives and to estimate repair costs or annualized costs for insurance purposes.

INTRODUCTION

Background. While performance-based design is one of the most promising ways to prevent loss of life and mitigate damage during natural hazards, its application to windstorms is currently challenging and has yet to be developed. In a performance-based design, buildings are designed and constructed to meet specific objectives, in terms life safety and the tolerable economic impact, at selected hazard levels. Performance-based design for ground shaking caused by earthquakes and is well developed for both existing buildings (ASCE 41-13 [ASCE 2014]) and for new construction (FEMA P-58 [FEMA 2012]). Compared to earthquakes, a similar application of performance-based design for windstorms is difficult, due to inherent differences in hazards, differences in hazard quantification, differences in basic design philosophies, and differences in modeling requirements used to assess performance.

The vulnerability ("fragility") of the building envelope during windstorms is especially distinct when compared to earthquakes. For ground shaking, the fragility of the building envelope is only dependent upon structural deformations induced by building motion, and in most cases the envelop fragility does not significantly affect the overall building performance. For windstorms the fragility of the building envelope dominates the overall building performance and depends on both deformations and water intrusion caused by wind-driven rain. Thus, the likelihood of water intrusion is dependent on deformation. The current performance-based design procedures lack these important modeling aspects crucial for windstorms.

Above all, there is a critical need to determine the vulnerability of the building envelope to combined structural deformations and wind-driven rain intrusion. Despite ever-evolving building code requirements and improvements in construction, windstorms—particularly hurricanes—continue to devastate communities and cause widespread damage. While much of this damage is related to sea-level rise (storm surge) and wind-borne debris striking the exterior of buildings, a significant amount of damage to the interior of buildings is linked to water intrusion caused by wind-driven rain (Smith 2017; Peraza et al. 2014). Water intrusion is not only a problem for coastal locations, but for inland locations as well. For example, the 2008 Hurricane Ike made landfall in Texas, but caused $1.5 billion in Ohio (Reinhold et al. 2011). Preliminary estimates indicate 2017 Hurricane Harvey has caused anywhere from $10 billion to $160 billion in damage. In the absence of a correct building envelope fragility, the application of performance-based design to windstorms will remain problematic, and the goal of protecting communities from both earthquakes and windstorms will remain elusive.

In residential buildings, roof sheathing failure during a windstorm has been a major source of damage and loss of functionality. Dao and van de Lindt (2012a,b) have proposed a method to estimate damage due to wind-driven rain using a theoretical-based water intrusion model (Dao and van de Lindt 2010). However, recent research of residential buildings subjected to wind-driven rain has established a direct basis for estimating the volume of rainwater intrusion. Based on experimental testing of small-scale buildings with a given set of openings in the building envelope the volume of water can be estimated (Baheru et al. 2014b). A method to simulate wind-driven rain in a large-scale wind tunnel associated with tropical storms and hurricanes and to determine the distribution and admittance of rain water was then developed (Baheru et al. 2014a,c), and the distribution and admittance of rain water can then be determined.

Objectives and Scope. The research described in this paper builds on prior research by correlating the water intrusion with the vulnerability of sheathing failure and integrating the results with the windstorm hazard for a given location. The overarching goal is to develop an analytical method that can be used to design residential buildings with wood panel sheathing that are resilient during windstorms. The specific objectives of the study are to (1) determine the envelope roof sheathing fragility for wind loads, and (2) correlate the fragility with water intrusion, and (3) predict the risk of water intrusion. The proposed method is illustrated for an archetypical residential building and focuses on roof sheathing, but the method is equally applicable to wall sheathing.

METHODOLOGY

Sheathing Fragility. In the proposed method, the fragility of wood panel roof sheathing subjected to straight-line wind loads is first determined. The preferred method is to calculate the wind loads based on experimental wind-tunnel testing. Several databases of tests conducted on small-scale models of buildings are publically available, including the Tokyo Polytechnic University database (www.wind.arch.t-kougei.ac.jp) and the National Institute of Standards and Technology (NIST) database (fris2.nist.gov/winddata/). These databases contain time series data of point wind pressure coefficients on the surface of a small-scale aeroelastic (rigid) building models. The models have pressure taps distributed over the roof and wall surfaces of the models, and the wind tunnels are configured with roughness elements and vertical spires to simulated terrain and the wind speed profile of the atmospheric boundary layer. Tests conducted on full-scale structures have also been conducted (e.g. at the Insurance Institute for Business and Home Safety (IBHS) Research Center, disastersafety.org/ibhs-research-center, and at the Florida International University (FIU) "Wall of Wind" facility, cee.fiu.edu/research/facilities/wall-of-wind), but generally the results are not publically available. If applicable test data, in terms of building length-to-width-to-height aspect ratio and shape (i.e. gable or hip roof) is not available, then ASCE 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE 2017), or an equivalent standard, may be used to estimate wind loads. The wind pressure as a function of time, $p(t)$ on the surface of the building can be calculated using Equation 1

$$p(t) \quad = \quad 0.5\rho {V_H}^2(Cp(t)) \tag{1}$$

where ρ is the mass density of air, V_H is the hourly mean wind speed (often referenced at the mean roof height) and $Cp(t)$ is the pressure coefficient that varies temporally and spatially.

The roof sheathing fragility is determined by calculating the probability that each sheathing panel will fail, based on the applied wind pressure and the uplift capacity of the sheathing panel determined analytically or experimentally.

Water Intrusion. In the proposed method, a semi-empirical model (Baheru et al. (2014a) is used to correlate the sheathing fragility with the volume of rainwater intrusion due to wind-driven rain. The intrusion model is based on three basic factors: the water pathways (i.e. defects, breaches, and functional openings in the building envelope), the source of water (storm type and directionality), and the driving wind force. The total volume of water due to wind-driven rain V_{tot}, is then be calculated using Equation 2, adapted from Baheru et al. (2014c)

$$V_{tot} \quad = \quad RAF * IR * A_b \tag{2}$$

where RAF is an empirically-derived "Rain Admittance Factor", A_b is the area of the breaches or openings, and IR is the total wind driven rain per vertical area of wall or projected roof calculated using Equation 3

$$IR = R * d \tag{3}$$

where R is the rainfall rate for a given location and d is the duration of the rain. The RAF has been determined experimentally for wind-driven rain associated with tropical storms and hurricanes and for three types of building roofs: flat, gable, and hip-roof (Baheru et al. 2014b). Comparison between observed and experimental wind-driven rain showed good agreement in terms of raindrop diameter, wind velocity, surface variability, and water output volumes Baheru et al. (2014b,c).

Risk of Water Entry. The sheathing failure and water intrusion are integrated with the windstorm hazard curve for a given location and exposure time in order to predict the risk of water entry. The wind speed associated with a windstorm can be described as a Poisson process. In equation 4, the probability of occurrence of an wind speed, N in t years is

$$P(N \geq 1) = 1 - e^{(-\lambda_a t)} \tag{4}$$

where λ_a is the annual mean windstorm exceedence frequency corresponding to an intensity measure (i.e. wind speed), the probability that the intensity of a windstorm, A will exceed some level, a in a given year.

$$\lambda_a = P(A > a \mid t = 1yr) \tag{5}$$

where λ_a is the annual mean windstorm exceedence frequency corresponding to an intensity measure (i.e. wind speed), the probability that the intensity of a windstorm, A will exceed some level, a in a given year. For low annual exceedance frequencies, Equation 4 is numerically equivalent to the hazard curve (inverse of MRI) expressed by Equation 5. Thus,

$$\begin{aligned} P(N \geq 1) &= \lambda_a t \\ &\lambda_a \end{aligned} \tag{6}$$

The sheathing failure curve is simply the probability of sheathing uplift failure, F conditioned on the occurrence of a wind speed value:

$$P(F|A < a) = \int_{-\infty}^{a} f(t)dt \tag{7}$$

where *f(t)* is the probability density function. The risk of water entry is based on the "risk integral"

$$\lambda_F = -\int_0^{+\infty} P(F|a)\left(\frac{d\lambda_a}{da}\right) da \tag{8}$$

Let

$$u = P(F|a)$$
$$du = \frac{dP(F|a)}{da}$$

where the latter is the same as

$$du = f(a)\, da$$

and let

$$dv = \left(\frac{d\lambda_a}{da}\right) da$$
$$v = \lambda_a$$

Invoking definite integration by parts:

$$\begin{aligned}
\lambda_F &= -\int_0^{+\infty} u dv \\
&= -\left[uv|_0^{+\infty} - \int_0^{+\infty} v du\right] \\
&= -[P(F|a)\,\lambda_a]_0^{+\infty} + \int_0^{+\infty} \lambda_a\, f(a)\, da \\
&= -[(1)(0)-(0)(1)] + \int_0^{+\infty} \lambda_a\, f(a)\, da \\
&= \int_0^{+\infty} \lambda_a\, f(a)\, da
\end{aligned} \tag{9}$$

Finally, the cumulative risk (P_F) of water entry during an exposure time (t_{exp} in years) is calculated using Equation 10.

$$P_F = 1-(1- e^{(-\lambda_F t_{exp})}) \tag{10}$$

EXAMPLE APPLICATION

The proposed method is illustrated for an archetypical 62.5-ft by 40-ft residential building in two locations: (1) an inland location in Omaha, Nebraska, and (2) a coastal location in Miami, Florida. The building has a 1:12 slope gable-shaped roof. The associated rainfall for these locations (Figure 1) was based on ASCE 7-16 using the companion "Hazard Tool." The 100-year rainfall for the Omaha location is 5.22 in./hr for a 60-min. interval, and 9.4 in./hr for a 15 min. interval.

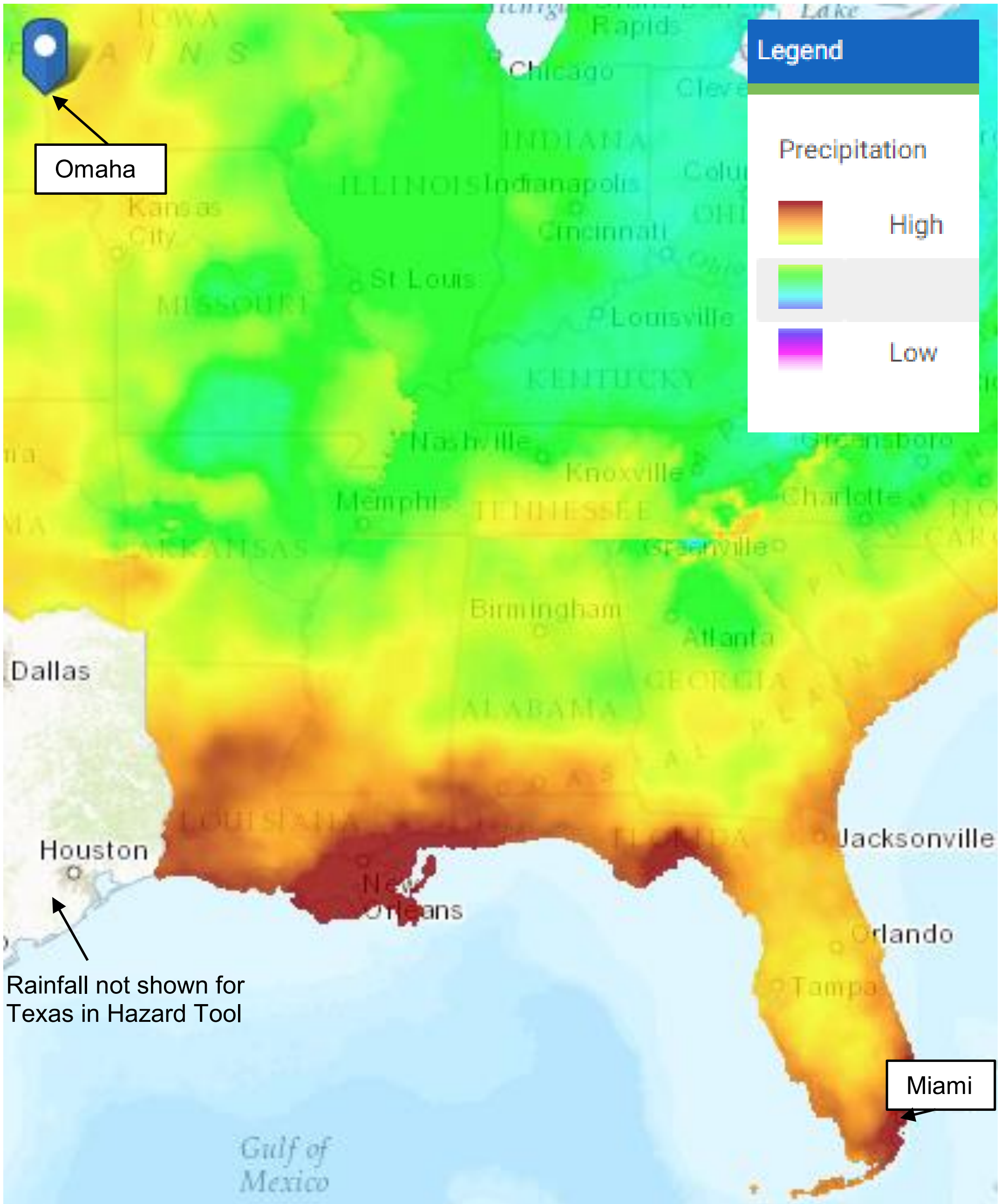

Figure 1. Qualitative map of expected rainfall generated using ASCE 7-16 (ASCE 2017) Hazard Tool https://asce7hazardtool.online/

The associated basic design wind speed (mph) for these locations was based on ASCE 7-16 using the companion "hazard tool" and the predecessor site used to determine wind speeds for various return periods (http://windspeed.atcouncil.org/). For example, Figure 2 shows a map of the design wind speed for a 300-year mean recurrence interval (MRI). The corresponding wind speeds for typically occupancy ("Risk Category II" structures) have a 700-year MRI and a strength-level wind speed equal to 110 mph for the Omaha location, and a strength-level wind speed equal to 169 mph for the Miami location.

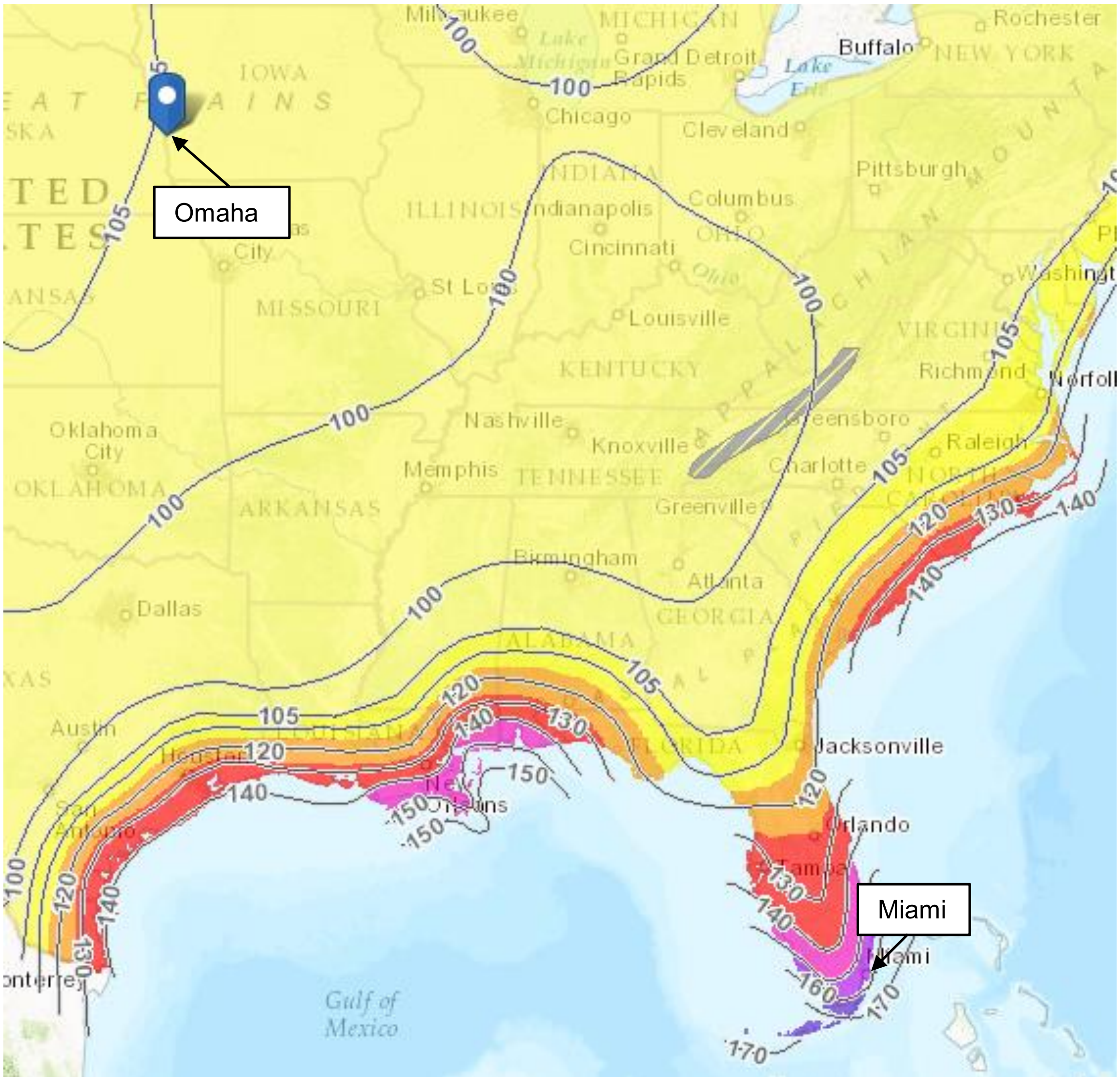

Figure 2. Wind speed (mph) contour map associated with a 300-year MRI generated using ASCE 7-16 (ASCE 2017) Hazard Tool
https://asce7hazardtool.online/

The roof sheathing panel fragility was based on wind tunnel testing of a small-scale model of the building (Hoq and Judd 2017) and experimental data from physical testing of wood sheathing panels (Lee and Rowowsky 2005). The panel tests comprised 4x8 ft sheathing consisting of 15/32-in. (12-mm) thick CDX plywood, fastened using 8d common nails with 6-in. spacing along panel edges and 12-in. spacing along interior lines. The sheathing thickness and nail spacing meet typical minimum code requirement, although oriented strand board (OSB) is more commonly used nowadays. The test data found that the mean wind uplift pressure required to fail one or several sheathing connections was equal to 57.7 psf with a coefficient of variation (COV) equal to 0.2. Other failure modes are possible (Henderson et al. 2013) but the focus in this study was on a nailed sheathing connection failure.

The total number of roof sheathing panels failed was based on the total uplift pressure q_z (psf) for each panel calculated using Equation 11.

$$q_z = 0.00256 K_z K_{zt} K_d V^2 \tag{11}$$

where K_z is adjusts pressure based on the height of interest (K_z is equal to 0.94 for 24-ft mean roof height), K_{zt} is the topographic factor (equal to 1.0 for no hill or escarpment), K_d is the directionality factor (equal to 0.85 for typical solid-bluff body structures), and V is the design wind speed (mph) for a given MRI. In order to convert wind tunnel pressure coefficient data to equivalent ASCE 7-16 pressure coefficient GC_p data, Equation 12 was utilized:

$$GC_p = \frac{\frac{1}{2}\rho(V^2_{h,z_0,mean\ hrly})C_p}{\frac{1}{2}\rho(V^2_{10m,OC,3sec\ gust})K_{zt}K_h K_d I} \tag{12}$$

where ρ is the density of air, $V^2_{h,z_0,mean\ hrly}$ is the mean hourly velocity referenced to the roof height z_0, $V^2_{10m,OC,3sec\ gust}$ is the 3-second gust wind speed at the roof height, and I is the "importance" factor (equal to 1.0 for typical buildings). The resultant envelope of GC_p values (Hoq and Judd 2017) are shown in Figure 3.

After the GC_p values were calculated for the roof sheathing panels, q_z was calculated for a range of wind speeds (70 mph to 170 mph). Since these GC_p values are envelope values, it was recognized that the calculated number of sheathing panels failed is more than would be expected for a given wind direction. As a result, the number of panels failed was multiplied by the directionality factor (K_d) equal to 0.8.

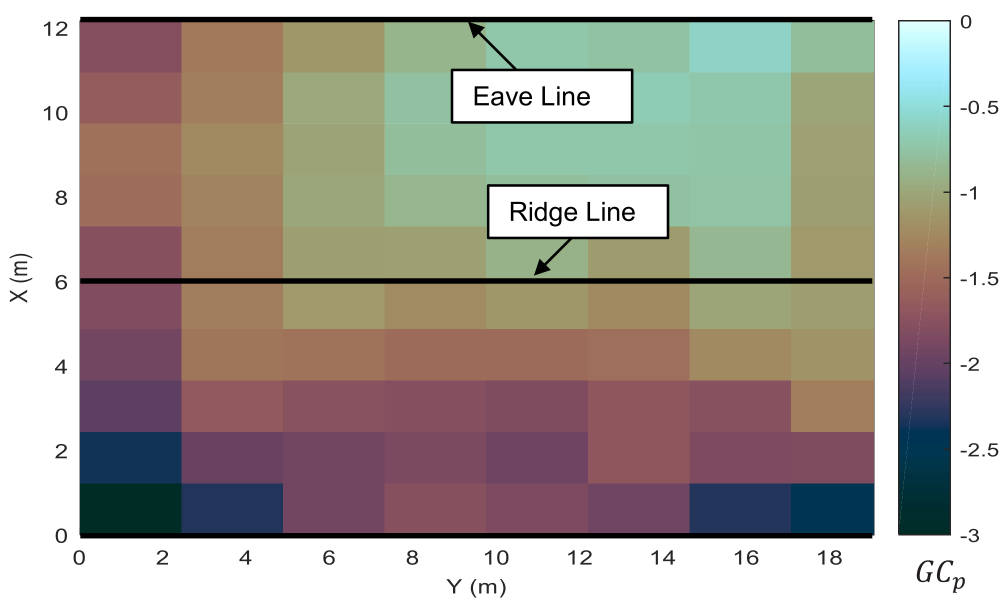

Figure 3. Equivalent ASCE 7-16 wind pressure coefficient GC_p values for roof.

The resultant roof sheathing fragility is shown in Figure 4. For instance, based on the fragility curve for a typical strength-level wind speed equal to 115 mph, approximately 10% of the roof sheathing panels are probable to fail. Figure 5 shows the windstorm hazard curves, in terms of the basic (3-second gust at 10-m height) wind speed, for the two locations. The maximum probable wind speed caps at approximately 110 mph, whereas the probable wind speeds for Miami reach over 170 mph. Figure 6 shows the "deaggregation" of hazard. The value of this intermediate calculation is that the plot clearly shows the range of wind speed that contributes the most to the annual risk of roof sheathing failure. Finally, Figure 7 shows the risk of roof sheathing failure over the exposure time, taken in this study as 50 years, equal to typical design lifespan of a residential building.

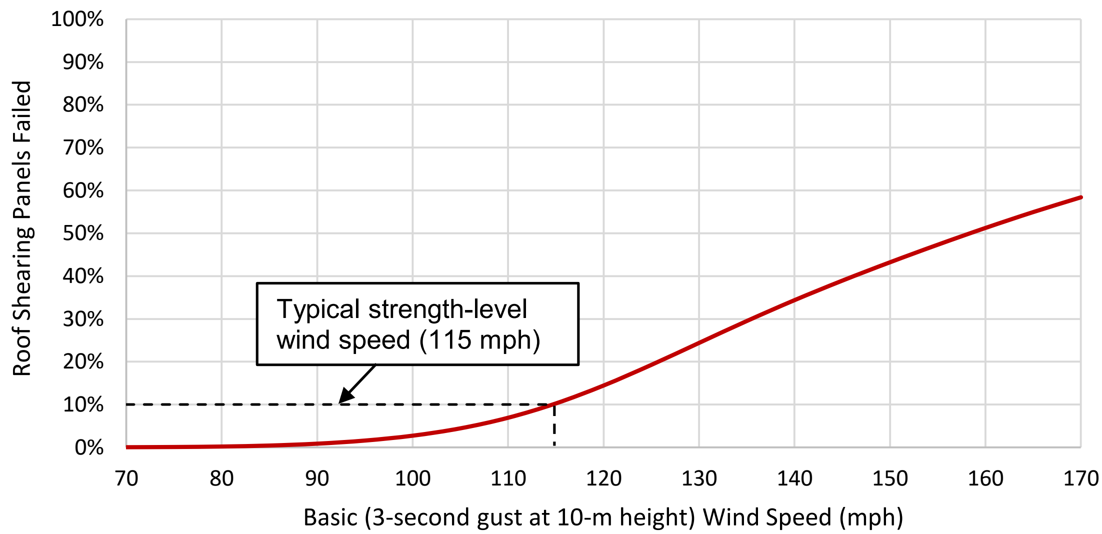

Figure 4. Roof sheathing fragility.

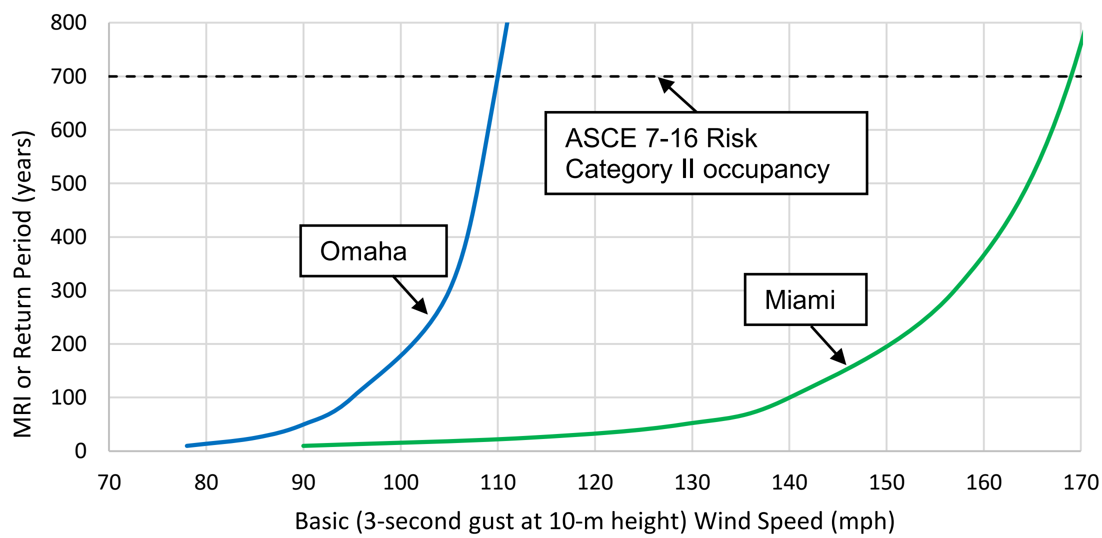

Figure 5. Wind hazard curves.

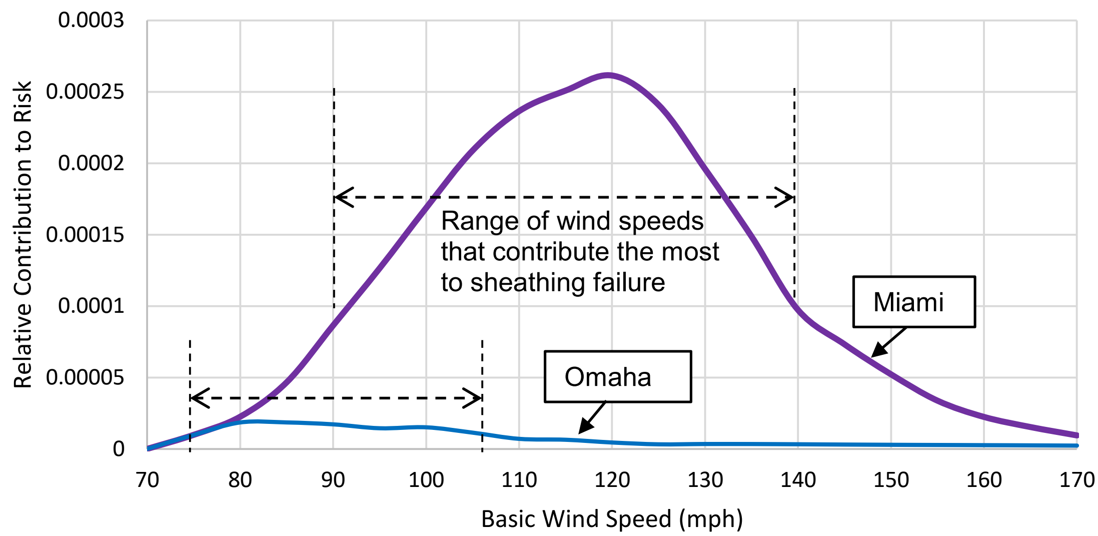

Figure 6. Risk of sheathing failure deaggregation (contribution to risk).

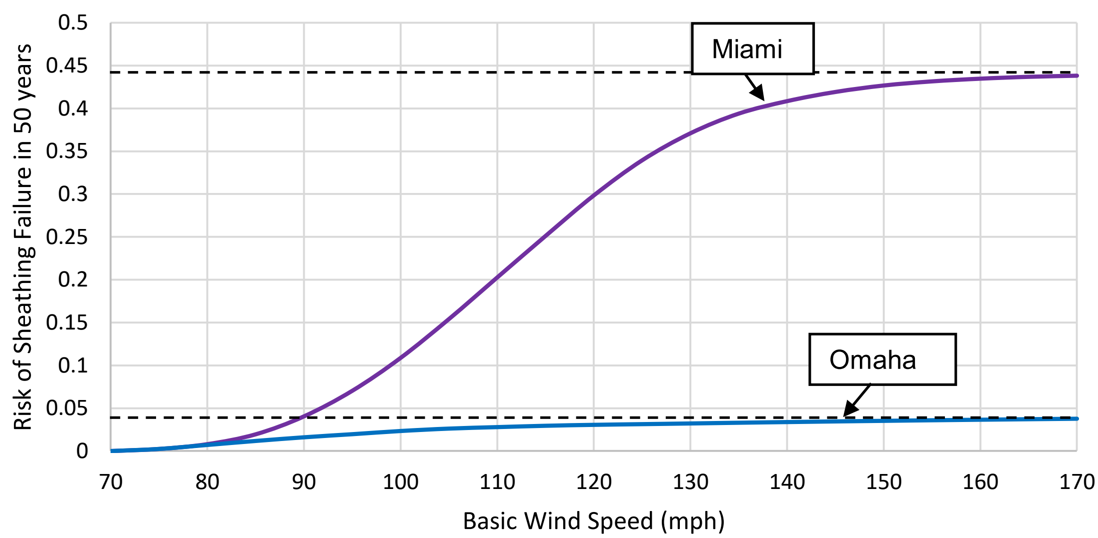

Figure 7. Risk of roof sheathing failure in 50 years.

Based on Figure 7, a *cumulative* total volume of infiltrated water entering the building over 50 years can be estimated for a storm with a specific wind speed. In order to calculate rainfall intrusion, Equation 2 was used. Since no particular wind direction is known in this example, the average of the *RAF* values from Baheru et al. (2014c) was used, equal to 0.19 for the roof surface, and the storm duration was taken as 60 minutes. The sensitivity of the method to the assumed use of average *RAF* values is examined in the following page. The final volume is based on A_b (the area of the breach) was assumed to be equal to the area of the number of sheathing panels failed (32 sf per panel). It was recognized that this assumption would lead to an upper bound in terms of the area of breach, as sheathing panels are not always *fully* removed when they fail.

For the Miami location, the IR is calculated using Equation 3:

$$IR = 5.22\ \frac{in}{hr} * \frac{1ft}{12in} * 1\ hr \qquad \text{(Miami)}$$

Using this IR value, the water intrusion volume can be calculated.

$$V_{tot} = (0.19)(0.435\ ft)(0.44)(32\frac{sf}{panel})(80\ panels) \qquad \text{(Miami)}$$

$$= 93 \text{ cf}$$

As a result, it can be expected that 93 cf (700 gallons) of rainwater would infiltrate the building over a period of 50 years, for an assumed 1-hour storm duration. Based on the maximum RAF value equal to 0.3 and the minimum RAF value of 0.05, the prediction of rainwater varies from 180 gallons to 1100 gallons. Thus, the method is very sensitive to the RAF value. Similarly, for the Omaha location:

$$IR = 3.72\ \frac{in}{hr} * \frac{1ft}{12in} * 1\ hr \qquad \text{(Omaha)}$$

$$V_{tot} = (0.19)(0.31\ ft)(0.0375)(32\frac{sf}{panel})(80\ panels) \qquad \text{(Omaha)}$$

$$= 5.7 \text{ cf}$$

Thus, it can be expected that 5.7 cf (42 gallons) of rainwater would infiltrate the building over a period of 50 years, for an assumed 1-hour storm duration. The range of rainwater could vary from 11 to 67 gallons, depending on the RAF value. Obviously, the Omaha location poses significantly less risk compared to the Miami location.

CONCLUSIONS

An analytical method to design residential buildings that are resilient during windstorms was presented in this paper. In the proposed method, the integration of fragility and hazard allows the risk of sheathing failure and consequent water damage to be predicted for a given building and location. Research conducted by Baheru et al. (2014a,b,c) was employed to calculate the total volume of water given a wind speed and rain intensity. This usage required assumptions regarding the storm-event duration and the rain intensity. The RAF values were empirically derived and in the example application, the values were averaged, since no particular wind direction may be known or predicted with accuracy. The area of breach was also based on the full panel size, which is probably greater than the area that would actual permit wind-driven rain to enter the building envelope.

For an archetypical 62.5-ft by 40-ft residential building in an inland location and in a coastal location, the analyses predicted that during a typical 50-year lifetime, the building located in Omaha could expect less than 50 gallons of water infiltration, whereas the building located in Miami could expect nearly 700 gallons of water infiltration. Although in this paper the repair costs and repair times associated with these volumes of water was not estimated, it is intended that the method would eventually be expanded to describe the consequence in terms of dollars and time. Then these consequences could be used to evaluate if the residential structure would be "totaled" (damaged with repair costs exceeding the property value).

The proposed method could be used to estimate likely damage caused by wind and wind-driven rain. However, before implementation of the proposed method, several areas need to be addressed. For instance, the area of the breach needs to be studied. In many, sheathing panel failure would only result in a small portion of the panel being lifted, so the area of the breach would be much smaller than the area of the corresponding panel. Moreover, the rain intrusion and wind damage estimates were evaluated only for the roof sheathing, but the effect of wall sheathing panels needs to be included. Another factor is that the RAF values were averaged and could be adjusted to account for spatial distribution, since minor adjustments have drastic effects. Lastly, a uniform rainfall rate was used to calculate the water intrusion for windstorm, but realistically the rainfall rate fluctuates over time. In this way, the method could also be used to design the roof sheathing panels to meet performance objectives, to estimate repair costs and repair times, or used to estimate annualized costs for insurance purposes.

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Eco- materials for Housing and Low Rise Building Construction

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ABSTRACT

The population explosion in recent decades has increased demand in the housing sector which in turn has exerted pressure on the natural resources. House being a basic need of human being has to be arranged to everyone by minimizing the exploitation of natural resources and maintaining the environmental balance. Reducing, reusing and recycling of building materials for construction are considered for energy, economic and environment benefits. This paper demonstrates few eco-materials and technology developed in India for housing construction. The properties of cement stabilized soil blocks (CSB) and construction of roof using coconut shell sandwich panels are illustrated along with their specifications. Comparison of embodied energy of CSB with other conventional masonry blocks illustrates its energy efficiency, economy and sustainability. These pre-fabricated blocks can be used for all type of masonry works as load bearing walls as well as partition walls. The application of coconut shell sandwich panels developed in NIT Calicut for roofing construction has been illustrated. These eco- construction techniques are suitable for housing and low rise structures.

Keywords: Sustainable construction materials, cement stabilised blocks, coconut shell sandwich panel, housing, low rise buildings.

1. INTRODUCTION

The construction activities have taken a large leap in recent years due to increased demand for the infrastructural facilities as a result of population growth. Natural resources have become scarce exploited to meet this growing demand in construction. The change of living standards and luxury add to the exploitation of the resources. Manufactured building materials which consume large quantity of energy such as steel, cement, glass, aluminum, plastics and bricks are commonly used for building construction. Increased use of these energy intensive materials will not only deplete the energy resources but also produce adverse environmental effects (Reddy 2004). As it is our duty to preserve the natural resources for the future generations, Eco-materials and sustainable techniques need to be utilized and implemented in construction industry to minimize the environmental impact and to maintain ecological balance (Kasthurba 2015). Housing construction in suburban and rural regions need to utilize locally available resources.

This paper outlines the engineering properties and specifications of few popular eco-materials for sustainable residential building construction in India. Load bearing walls using cement stabilized soil blocks (CSB) and roof construction using coconut shell sandwich panels are illustrated. Comparison of embodied energy of CSB with other conventional masonry blocks illustrates its economic and sustainable attributes. These blocks can be used for all type of masonry works as load bearing walls as well as partition walls. The technique of using coconut shell panels developed in NIT Calicut is recommended for cost effective housing and low rise structures. These construction methods are recommended for low income group housing by active participation of beneficiaries in construction activities through short term training.

2. Eco- materials for Construction

International construction research networking organization CIB in 1994, defined sustainable construction as “creating and operating a healthy built environment based on resource efficiency and ecological design.” The main aim of sustainable construction is to minimize natural resource consumption and also the impacts on ecological systems (Kibort 2013). Concentrating more on sustainable materials and technologies could reduce the adverse effects on environment and reduce the energy usage. The growing demand for materials in building industry cannot be fully met by the natural resources or energy efficient traditional materials. Hence there is a need to utilize available alternatives and techniques to solve the increasing needs in construction.

Masonry materials is the most abundantly required building material in housing construction. The material may be load bearing or non-load bearing depending on the application and technique of manufacture. Study on laterite masonry blocks a popular housing construction material and their properties are outlined. Comparison of various popular masonry materials available in the construction industry is also reported.

2.1.Laterite masonry blocks

Laterite is a tropical weathered rock occurring worldwide, existing abundantly in parts of India. It is a masonry material predominantly used in western coastal region of India that includes Goa, Karnataka and Kerala. Laterite is a rock which hardens as it is exposed to atmosphere and is advantageously used as a load bearing masonry material in Malabar area of Kerala. Laterite mining was carried out manually with axe in the past, but new power cutting machines are developed for easy cutting and to get equal sized blocks. They are usually obtained in a size of about 330mmx200mmx200mm. Laterite blocks are heavy (about 35 to 40 kg) and this makes it difficult for masons to work with laterite. They contain mineral oxides of Iron and Aluminium. Laterite is generally reddish in color. As it is cut into required shape and size manually, thermal energy requirement for manufacturing of blocks is negligible. However, transportation cost is to be considered for the transportation of material from mining site to construction site. The expenditure for production of laterite blocks include the land cost, labor for excavation and labour for shaping and sizing.

2.2. Stone blocks

Natural stones are of great use in construction industry in India. They are used as masonry material, foundation material, etc. Stone blocks are generally obtained by breaking huge natural stones into smaller sizes. Stone blocks are usually available in sizes of 180mmx180mmx180mm and this size blocks are used for masonry purposes. The sizing is done manually. But the breaking of huge size natural blocks are sometimes done with the help of detonators. Hence, thermal energy required for manufacturing is much less. However, transportation cost is to be considered for the transportation of material from mining site to construction site. The expenditure for production of stone blocks include the quarry land cost, labor and machinery for breaking of huge natural stones and also labor for shaping and sizing. There is no need of transportation cost as the blocks are made from the mining site itself.

2.3. Burnt clay bricks

They are the most common masonry material used in India. It is estimated that about 70 billion bricks are produced annually. They are available in different sizes like 230mmx105mmx70mm, 200mmx90mmx90mm etc. They are manufactured from red clay. Manufacturing process involves high thermal energy for burning of bricks. Coal, coal cinder, firewood, etc. are commonly used as fuels for burning. For a size of 230mmx105mmx70mm, each brick requires 0.20 kg of coal or 0.25 - 0.30 kg of firewood for the burning process. This is equal to a thermal energy of 3.75 - 4.75 MJ per brick (Reddy 2003). An average of 4.25 MJ per brick has been considered for the comparison of energy content of buildings. The expenditure for production of burnt clay bricks includes cost of clay and water, labor for mixing and moulding, cost of fuel and labor for high temperature burning of mix. Transportation charge of the materials from the extraction site to the moulding place also adds to the cost and expenditure.

2.4. Soil-cement blocks

Soil- cement blocks are manufactured by pressurized pressing of wet soil-cement mixture in required sized mould. Mechanized pressing units and manual pressing units are available. Soil–cement blocks produced by employing manually operated machines in a highly decentralized fashion have become increasingly popular in India and elsewhere (Jagadish 2008) (Walker 2000). As cement content is present in the blocks, the energy content depends on the cement percentage used. The thermal energy of cement is 5.85 MJ/Kg. Load bearing soil cement blocks will have a cement content of about 6 - 8%. Such blocks will have an energy content of 2.75 - 3.75 MJ per block of size 230mmx190mmx100mm (Reddy 2003). The expenditure for production of soil - cement blocks contains the cost of materials, which includes soil, cement and water, labor and machinery cost for mixing and moulding, and curing charges. Transportation charge of the materials from the extraction site to the moulding place also adds to the cost and expenditure

2.5. Hollow concrete blocks

Hollow concrete blocks, generally called as hollow blocks are light weight blocks manufacture by pressing concrete of 6 -10mm coarse aggregates in sized moulds. Hollow concrete blocks are non-load bearing blocks used generally for partition and for masonry works of multi- storeyed buildings in India. Similar to soil cement block, the energy component of hollow concrete blocks depends on the cement content. Also the energy for crushing coarse aggregates to required size will also add to the total energy. Cement percentage of hollow concrete block is generally 7 -10% by weight. Hollow concrete blocks are usually available in size 400mmx200mmx200mm and the energy content of the block is 12.3 - 15.0 MJ. The expenditure for production of hollow- cement blocks contains the cost of materials, which includes coarse aggregates, fine aggregates, cement and water, labor and machinery charges for mixing and moulding, and curing charges. Transportation charge of the materials from the extraction site to the moulding place also adds to the cost and expenditure.

The energy content of the above mentioned masonry materials are given in Table 1. The table contains details on type of blocks, size of blocks, energy content of the specified size, energy per brick equivalent and percentage of energy with respect to brick energy (Reddy 2003). All bricks are of different sizes and for easy comparison they have been normalized by referring to an equivalent size. Equivalent size is chosen as 230mmx105mmx70mm.

TABLE 1: Energy in Masonry Blocks

Type of Block	Size (mm)	Energy in one block (MJ)	Energy per brick equivalent	Block energy %
Laterite Block	330x200x200	0	0	0
Stone Block	180x180x180	0	0	0
Burnt clay bricks	230x105x70	4.25	4.25	100
Soil cement blocks	230x190x100	3.5	1.35	32
Hollow concrete blocks	400x200x200	15	1.62	38

Based on the data presented in the Table 1, the following inferences have been drawn:

1. Laterite blocks and stone blocks do not consume any energy in their production.

2. Burnt clay bricks consumes the highest energy during production.

3. The energy consumption by soil-cement block and hollow-concrete block is almost same with hollow concrete block having a little high value. Both comes to about 30 to 40% of burnt clay bricks.

3. Documentation of coconut shell sandwich panel construction

The project of coconut shell sandwich panel construction was undertaken in the year 2008 by NIT Calicut in a suburban panchayat (Kakkodi) 6 kilometers from Calicut city. The project on Skill up-gradation of rural craftsmen and women workers was funded by AICTE-TEQIP and implemented jointly by NIT Calicut and Saraswat Institute, Kakkodi Panchayath, Kozhikode district. The training for the coconut shell sandwich panel construction was carried out by masons and women workers at Kakkodi region through instructive demonstration. The demonstration of coconut shell sandwich panel was undertaken for the construction of a vaulted structure with dimensions of 2.4m x 1.8m in plan and a height of 2.7 m. Coconut shells (waste material after removal of coconut) were collected from the locality. The construction steps included- making a hole in the center of each of the hemispherical part of split coconut shell using ordinary drilling machine. The coconut shells are held together by stacking closely using a string wire. A formwork (re-usable one) made of steel pipe was made as per the required dimension (by industrial fabrication). The formwork is fixed on a laterite basement structure of 60-cm height. A welded wire mesh is spread over the formwork. The coconut shells in flexible string are placed in rows touching each other till the formwork was completely covered. A thin layer of Ferro cement concretewith 10 mm aggregates was laid after placing a flexible chicken mesh layer. The figures given below illustrates the step by step procedure involved in coconut shell sandwich panel construction.


Figure.1 a. Fixing the form work for construction on a laterite basement
b. Laying strings of coconut shell on top of welded wiremesh

Figure. 2 a Adding more coconut shell in parallel strings touching each other
b. Fixing of chicken mesh on top of the coconut shells to hold it firmly

Figure 3 a. Thin layer of concrete cover (2-3 cm) laid is on top
b. Final finishing using cement mortar (in March 2009),Work being supervised by the Director NITCalicut and co-ordinators

4. CONCLUSION

The embodied energy and factors affecting the cost and expenditure of different masonry materials has been discussed in this paper. The broad conclusions arrived after the study are as follows:

i. Stones that are formed naturally in nature are more energy efficient than other manufactured bricks, i.e., laterite blocks and stone blocks have zero embodied energy in their manufacturing process. But the availability of such natural materials in bulk quantities to meet the demand of the present world is often difficult. The resources are depleting day by day and the formation of hard laterite takes years.

ii. Burnt clay bricks have the highest embodied energy as compared to other masonry materials in the process of manufacturing. For a volume as low as 0.0017M3 of burnt clay brick, the energy is 4.25 MJ. This implies that the energy for 1 M3 of burnt clay brick consumes 2500MJ of energy for production only.

iii. Soil cement bricks are the most energy efficient masonry material among the artificially manufactured items. Their embodied energy is only about 30% of the embodied energy of burnt clay bricks. Cement content is the major reason for the consumption of energy in the manufacturing process. Energy can be considerably reduced if the cement content is decreased. New technologies have to be developed or new binding materials with lesser energy consumption have to be introduced as an alternative to cement.

iv. Energy consumption of hollow concrete blocks is comparable with that of soil cement blocks. But the availability and production of raw materials for concrete is a challenge. Also requirement of cement adds to embodied energy. Use of energy efficient materials reduces the embodied energy to a considerable amount.

v. Environmental impact on mining, excavation, burning, etc. has to be addressed during the manufacture of masonry blocks. High volume of CO_2, which is a green house gas, is produced in such activities. Atmospheric pollution caused by this is a threat to eco system. Also production of high energy materials needs fuel and raw materials, which results in depletion of non renewable natural resources.

vi. Most of the masonry materials available in the market are uneconomical. The main reasons being that the raw materials are scarce and costly. Natural resources is depleting and demand is increasing. Also cement content has a direct impact on the cost of masonry materials.

vii. Need for standardization of masonry material is very much significant. The embodied energy has to be reduced as much as possible. Materials have to be energy efficient, economical, sustainable and structurally stable. Selection of materials has to be carried considering all the mentioned factors.

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Economic Implications of Nanotechnology Adoption for Traditional Construction Materials

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ABSTRACT

This article examines the economic implication of adopting nanotechnology principle in the construction industry with a view to improving overall delivery of construction projects and enhance economic development. Previous literature materials on nanotechnology and their economic importance were reviewed with a view to obtain necessary variables for the study. Based on the obtained variables, the study adopted a survey method and quantitative data were collected through the administration of structured closed-ended questionnaires on stakeholders and professionals in the construction industry. The most important economic benefit of adopting nanotechnology is its ability to reduce financial requirements and various cost associated with infrastructural development. It will also be useful for instilling economic change and formulation of new economic opportunities for the construction industry. This therefore underscore the need for concerned stakeholders in the construction industry - including clients, construction professionals, contractors and various regulatory agencies - to embrace the use of nanotechnology to improve the economic contribution of the industry.

Keywords: Construction process; Economic development; Nanotechnology; Project success; Sustainable construction.

INTRODUCTION

Doubtlessly, nanotechnology has gotten to be one of the powerful advances in this century since it has been fruitful in interesting all manifolds of innovation, and it is becoming popular in the architecture, engineering and construction industry. The construction industry finds more particularly its advantage with nanotechnology because of its need for more material and energy resources. With regards to all materials utilized as a part of development and construction in the industry, concrete possesses about seventy percent of the materials with regards to volume and this indicate the importance of the material. However, the adoption and usage of nanotechnology help in creating more solid and strong material than ordinary ones (Rao et al., 2015).

Human abilities, expectation and vision to control the material world has been changed by the growing emerging technology known as nanotechnology (Sobolev et al., 2006). It appears to hold the key that permits development and building materials to imitate the components of common frameworks enhanced until flawlessness amid a huge number of years (Pacheco-Torgal and Jalali, 2011), and furthermore, opens new routes linked to new efficient, intelligent and better performing materials following new pathways of production, and towards new structural designs and related maintenance and monitoring systems (Péro, 2004).

ECONOMIC IMPORTANCE OF NANOTECHNOLOGY

Materials have been central to economic growth and societal advancement since the beginning of time. Furthermore, materials research can provide new solutions capable of optimizing the application of current technologies, minimizing their negative side effects and reducing production costs. Moreover, new materials developments usually have a very large economic leverage, thanks to their vast application breadth. They also produce a multiplying economic effect by stimulating additional demand for new processing and manufacturing equipment (Cahill, Hernández, and Bellido, 1999).

According to Canton (2007), there is no existing economic theory adequately very much created to comprehend the effect of innovation and science on the economy, in spite of the fact that there might be another post-modern economy molded by nanotechnology, and in view of controlling matter on-request, along these lines essentially changing the items, administrations, markets, stations, occupations, and supply chains that we know today (Gower, 2001). Ofori (2000) further states that the economies of numerous developing nations are at present went up against by serious troubles inferable from a mix of lower product costs, higher energy costs, falling exchange rates and continuously escalating inflation. In the meantime, the nation is confronted by gigantic social issues (counting a rising urban populace and unemployment) which are putting weight on the country's assets and capacities. The construction industry in a typical developing country is confronted diminished by levels of demand as an after effect of adjustment projects which perpetually include cuts in governments' capital investment. The test, as Ofori (1993) proposes, is that the development business ought to do well notwithstanding the extreme limitations in its working surroundings. Besides, the development business must help the national economies to recoup, and moreover add to the encouraging of the social issues.

As in all business sectors, innovation and moving demographics offer ascent to changing business sector requests. Materials and items utilized as a part of lodging development are not immune to these changes. Since a home or a business building is normally the biggest purchase a family will make and one of the bigger ventures a company will make, customers need structures that keep up their worth after some time and are protected and secure, healthy, comfortable, long lasting/dependable (durable), low maintenance, affordable (lower in expense and giving more esteem to the rand), effectively versatile to new and modified architectural designs, and take into consideration the idea of personalized customization, having improved and more technologically advanced system capabilities, and reduce costs for heating and air conditioning (Wegner et al., 2005).

This emerging science/technology has the core impact of instilling economic change. Economic change in this case may be portrayed as the development of capital, the innovation of new items and administrations, the rise of new markets, and the creation of riches. Moreover, the detailing of another financial open door, for example, work creation, and speculation potential would be normal for these progressions as well (Canton, 2007). Furthermore, Zhu at al. (2004) suggest that the greatest impact to the construction industry and the economy within this time frame is likely to come from enhancement in performance of materials stemming from better understanding and control at the nanoscale and improvement of production processes, due to the huge quantities of materials involved. The advances are likely to be incremental on existing materials and technologies.

It is becoming clear that if nanotechnology applications and nanotechnology continuously become core scientific and technological advancements, they also may represent the next evolutionary economic shift as well. Nanotechnology and nanomaterials with applications in the construction industry are at various phases of development ranging from conceptual ideas to commercially available products. However, awareness that follows the applications of nanotechnology in construction is considerably low among industry personnel (van Broekhuizen et al., 2011), hence construction has lagged behind other industrial sectors, such as automobile, chemicals, electronics and biotech sectors where nanotechnology research and development has attracted has pulled in noteworthy premium and speculation from vast modern organizations and investors (Zhu et al., 2004).

Nanotechnology is one of the core technologies that are and may create an evolution in global market value, driving innovation through the directly instilled fusion of business and technology (Canton, 2007). Moreover, it will encourage businesses that do not have their building blocks through previous economy such as oil, steel, capital, etc. but rather a creation of completely new business drivers, much like the direct economic implications it will have when applied to traditional construction materials and what can be achieved through them. According to Mangematin and Errabi (2012) is anticipated that the future economic impacts of nanotechnology will be considerable. This then also answers to the direct considerable impacts the application of nanotechnology will have to the construction industry economy when applied to traditional materials

Innovation has frequently assumed a focal part in riches era and the developing nanotechnology showcase can possibly change and reshape every single economic sector, from the essential to the tertiary. In any case, the supposition that nanoscience and its determining advancements will change the world must come from a fundamental commence, specifically that novel discoveries and developments in the nanometre scale will have an unmistakable and critical effect on profitability and productivity (Bürgi and Pradeep, 2006). In addition, breakthroughs in nanoscale science and engineering can launch and sustain systematic economic progress (Roco and Bainbridge, 2005). Nanotechnology will bring down input costs in some major industries, drastically enhance profitability and productivity in others, make completely new businesses, expand demand for a newly enhanced products and lower demand for others. The net result will be altogether expanded genuine wages and expanded way/standard of life, with just a transitional increment in unemployment as work and capital are moved to new, more important uses from those that have been superseded and made less profitable (Roco and Bainbridge, 2005).

The anticipated outcomes of quickly propelling advances on the nanometer scale will see the ascent of new enterprises and the fall of those continually inclined to conventional or sustaining technologies of the past (Cristensen, 2013). Showcasing of logical revelations at the wildernesses of science and mechanical advancements in the nano domain will turn into the main impetus of the nanomarket. Therefore it can be assumed that in the years to come, this generally new economic wonder will add to an expansion of the worldwide Gross Domestic Product (GDP) as anticipated by worldwide economic organizations like the World Bank and International Monetary Fund (Bürgi and Pradeep, 2006). In addition, Zhu et al. (2004) states that immense potential has been anticipated for nanotechnology applications in the construction industry and even minor enhancements in materials and procedures could bring expansive accumulated benefits. In the short to medium term, the greatest impact to the construction industry and the economy is likely to come from enhancement in performance of materials. In the medium to long term, nanotechnology development will prompt really progressive ways to deal with plan and creation of materials/structures with much improved adaptability to environmental change, energy efficiency and sustainability. Furthermore, the social promises and economic opportunities of nanotechnology and its applications are of great importance for human beings with relevant consideration being put to the impact they would have on the lives of many in terms of wealth creation and quality (Karaca and Öner, 2015).

NANOTECHNOLOGY AND THE CONSTRUCTION INDUSTRY

The applications of nanotechnology in the construction industry show to have a wide-reaching spectrum such that they could also be used to improve the generic design and construction processes in so many ways due to the fact that the products modified through nanotechnology would have more unique and defined characteristics (Hamus and Harris, 2013 and Rana et al., 2009). According to Halicioglu (2009), novel construction materials could be discovered as a result of the application of nanotechnology (e.g. given the usage on nano-fibres, nano-tubes and nanoparticles), to offer unique combinations of strength, toughness, strength and durability. The related examples include the creation of bio-mimetic material having their compositional and structural basis derived from elements found in nature, composites with self-adjusting interfaces, shape memory, self-repairing and strain hardening materials.

The primary and basic properties of traditional construction materials can be improved through nanotechnology, for example concrete, the functional capacity of existing materials may be enhanced (for example, self-cleaning, antimicrobial and properties for pollution reduction may be instituted in materials like coatings/paints or glass) and 'new' materials to fill existing needs will be introduced (for example, thin or transparent insulation through silica aerogels, or nanocapsulated corrosion inhibitors for steel erosion protection) (Hamus and Harris, 2013). In addition, these incorporate items that are for: lighter structures; more grounded basic composites e.g. for extensions and so on; low upkeep covering; enhancing channel joining materials and strategies; better properties of cementitious materials; lessening the warm exchange rate of flame retardant and protection; expanding the sound retention of acoustic safeguard and expanding the reflectivity of glass (Rana et al., 2009). According to Andersen and Molin (2007), technological developments in the construction industry have innovations through nanotechnological applications directly depended on them. Furthermore, since materials form part of the core business in the construction industry, the benefits of nanomaterials are sure to be realized given the idea that nanotechnology has the full capacity to influence exceeding and great innovations in structural design and the related innovations in buildings. Arivalagan et al. (2011) further emphasizes that construction can be made faster, cheaper and safe through the related nanotechnological applications. In addition, the construction of structures from advanced homes to skyscrapers can be achieved much more quickly and at reduced costs through the inclusion of nanotechnological advancements in construction.

According to Sobolev et al. (2016), nanotechnology is utilized to describe the two main routes followed in relation to the nanotechnology of construction materials are nano-engineering (nanomodification) and nanoscience. Nanoscience through the usage of relevant and advanced methods of characterization and modelling at atomic and molecular level, manages the estimation and portrayal of nano and smaller scale structure of materials utilized to understand how this structure affects the macro scale properties and performance. Nano-engineering incorporates the strategies of control and manipulation at the nanoscale to develop composites that are multifunctional with exhibit great performance mechanically, and exerting new generation special properties that are highly durable and have the potential to also exert novel properties such as self-healing, self-cleaning, self-sensing and the possibility of low electrical resistivity (Sanchez and Sobolev, 2010).

Traditional construction materials, such as concrete, asphalt, plastics and steel, are used on a large scale and produced in huge quantities. Historically, it has been possible to assess the properties of such materials only on macro-scale. For example, cementitious materials have existed for over 2000 years and at the moment a person utilizes more than 2 tons of concrete on average around the world annually. Furthermore, despite their undisputed importance, omnipresence and low-tech status, however, cement-based materials are among the least well-understood materials due to their complex nature. The time-dependent nature of the processes of cement or binding causes such complex structure to be viewed as even more complicated the processes of which when the clinker minerals of cement are mixed with water and can be continued for months and even years. Therefore, fundamental understanding at the nanoscale of the development and behavior of the cement matrix and its interaction with the other constituents and the environment can provide a systematic and cost effective means to develop superior concrete and to better control properties and degradation processes (Zhu et al., 2004). Furthermore, according to Rao et al. (2015), making or improving concrete through nanotechnology refers to utilizing the appropriate methods to add and produce nanoparticles in concrete at the most suitable proportions, with the improvement of the compressive and flexural strengths at early age being the basic premise and purpose, with its possibilities being high because of the high surface to volume ratio. Rao et al. (2015) further continues to state that nanotechnology, through nanosized materials, likewise enhances the pore structure of concrete, helps diminish permeability as they retain less water contrasted with customary cementitious materials and that the reduction of the cement content in concrete will be reduced by the existence of nanomaterials presence of nanomaterials which in turn will make the concrete far more different from the conventional concrete.

The potential advantages and impacts of nanotechnological applications in the construction industry are vast, and such applications represent the link of materials science and engineering towards enhancing the innovative capacity of the industry. Subsequently, these potential uses and advantages of nanotechnology in construction development will offer new and key routes towards enhanced construction innovation in building design and construction.

Nanotechnology play a key role in innovative approaches used in new building design and construction (Halicioglu, 2009). The basic knowledge generated by the nanoscience can be transformed into specific applications to create a new class of multifunctional high performance construction materials. Multi-functionality means the emergence of properties additional to those that normally define a material, by nano-modification (through nanotechnology) traditional materials or incorporation of functional nanostructures in them, materials can extend their range of applications (Porro, 2004:27).

RESEARCH METHODOLOGY

This paper examines various economic advantages of adopting nanotechnology for construction process and activities in the South African construction industry. To achieve the objective, survey design was adopted through the distribution of questionnaire to construction professionals working with construction and consulting firms in Gauteng region of South Africa. The targeted groups of respondents for the study include architects, construction managers, engineers, project managers as well as quantity surveyors that are involved in the planning, design, execution and management of construction projects in Gauteng Province of South Africa. To obtain necessary and relevant information, purposive sampling was employed to sample 64 respondents including chemical engineers with experience of construction activities and concept of nanotechnology as applicable to the construction industry.

The questionnaire was designed in two parts: the first address necessary background information while the main part was designed to obtain information from respondents on the economic importance of adopting nanotechnology in the construction industry. Identified economic importance of nanotechnology from literature were highlighted in a table and 5-point Likert scale was adopted to seek the opinions of respondents. Cronbach alpha value of 0.846 computed for the thirteen identified factors indicate that the adopted instrument and scale were satisfactory in measuring the opinions of respondents. Mean item score (MIS) and standard deviation (SD) were further calculated for each of the identified variables based on the adopted Likert scale, and the methods were used to rank and determine the economic importance of adopting nanotechnology in the construction industry.

FINDINGS AND DISCUSSION

Figure 1 shows the profession of respondents out of which 15% are construction project managers, 42% are quantity surveyors, 18% are construction managers, 15% are engineers while the remaining 11% are architects.

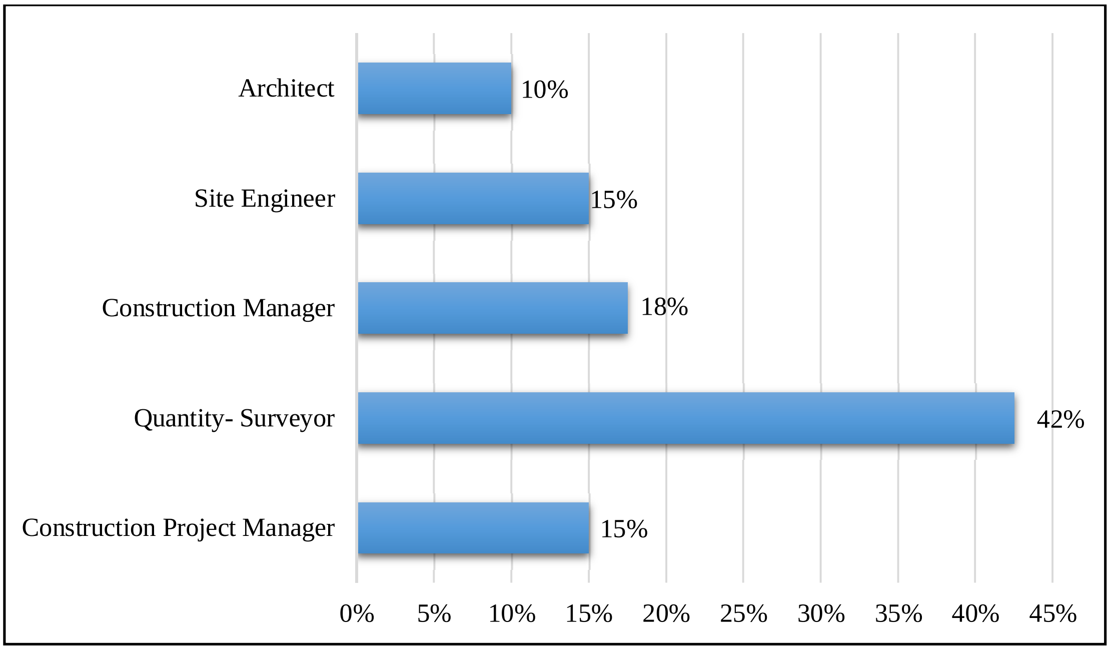

Figure 1: Profession of respondents

Table 1 shows the respondents' ranking of the economic implications of applying nanotechnology to traditional construction materials in Gauteng, South Africa. It revealed that its ability to reduce the related requirements and costs associated with infrastructure was ranked first with a MIS of 3.96 and a SD = 0.77; instil economic change in the construction industry was ranked second with a MIS of 3.85 and a SD = 0.78; formulation of new economic opportunities was ranked third with a MIS of 3.83 and a SD = 0.71; these were ranked fourth: sustain systematic economic progress with a MIS of 3.79 with a SD = 0.89, invent new products and services with a MIS of 3.79 and a SD = 0.72 and job creation with a MIS of 3.79 and a SD = 0.82; improve material production processes was ranked fifth with a MIS of 3.77 and a SD = 0.85; enhance profitability and productivity was ranked sixth with a MIS of 3.75 and a SD = 0.81; these were ranked seventh: create a new construction economy with a MIS of 3.73 and a SD = 0.74, and, enhance the construction materials market with a MIS of 3.73 and a SD = 0.69; minimizing production costs for materials was ranked eighth with a MIS of 3.63 and a SD = 0.77; aid production of wealth was ranked ninth with a MIS of 3.62 and a SD = 0.72, and stimulate demand for new materials was ranked tenth with a MIS of 3.52 and a SD = 0.70. The Cronbach's Alpha (α) for this section became 0.897.

The findings with regard to the utilized Likert scale and the obtained Mean Item Scores reveal that for the economic implications ranked from first to the ninth the respondents agree with the advantages except for the last economic implication in the revealed findings, where the respondents show a neutral capacity. This conclusion is brought forth by the interpretation of the MIS with an assumption that for a MIS below or equal to 3.55 the respondents either reflect that they strongly disagree, disagree or a neutral capacity towards the question. Furthermore, for a MIS beyond 3.55, the respondents reflect that they agree and strongly agree with the question.

Table 1: Economic Implications of Nanotechnology

Variables	MIS	SD	R
Reduce the related financial requirements/costs associated with infrastructure	3.96	0.77	1
Instil economic change in the construction industry	3.85	0.78	2
Formulation of new economic opportunities	3.83	0.71	3
Sustain systematic economic progress	3.79	0.89	4
Job creation	3.79	0.82	4
Invent new products and services	3.79	0.72	4
Improve material production processes	3.77	0.85	5
Enhance profitability and productivity	3.75	0.81	6
Create a new construction economy	3.73	0.74	7
Enhance the construction materials market	3.73	0.69	7
Minimizing production costs for materials	3.63	0.77	8
Aid production of wealth	3.62	0.72	9
Stimulate demand for new materials	3.52	0.70	10

SD = Standard Deviation; MIS = Mean Item Score; R = Rank.

The findings are in agreement with studies done by Roco and Bainbridge (2005) stating that such applications will generally reduce the related financial requirements/costs related with infrastructure and continue to launch and sustain systematic economic progress. The systematic progress aided by the enhanced productivity and productivity, expanded demands for newly enhanced products/materials, etc. The findings further substantiate positively to the studies carried out by Steinfeldt et al. (2007) and Canton (2007) that these applications to the materials will make further strides to more tangible economical business in construction, and increase the overall need for more sustainable infrastructure development.

CONCLUSION AND RECOMMENDATION

The aim of this study is to examine the economic implications of nanotechnology adoption with a focus on construction design, execution and materials in Gauteng Province, South Africa. The findings from the questionnaire study obtained from the respondents showed that to reduce the financial requirements/costs associated with infrastructure, instill economic change in the construction industry, formulation of new construction related economic opportunities and job creation are the most significant implications of applying nanotechnology to construction activities. Applying nanotechnology will result in noteworthy economic progress and growth, such that it will lower production costs. Nanotechnology is an emerging technology which has the potential to produce a multiplying economic effect by stimulating demand for new processing and manufacturing equipment. Thus, there is a need for more awareness and understanding of the usefulness and effects of adopting nanotechnology in the construction industry. This can be achieved through research collaboration between the academic institutions and the industry, training and development of construction stakeholders including professionals, contractors and regulatory agencies, workshop and conferences on application of technology to construction activities as well as creating opportunities for adoption of new materials and methods in the industry.

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A system dynamics modelling of occupants' thermal comfort in dwellings

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ABSTRACT

In temperate regions, about 90% of the time is spent indoors. Indoor thermal comfort can be predicted with the use of a number of environmental parameters like temperature, humidity and the likes. Previous research efforts involving occupants' thermal comfort (OTC) have immensely benefitted from building physics and numerical simulation models. This study advocates a shift in OTC modelling paradigm to include a model based on both qualitative and quantitative data. The research explored the intrinsic interrelationship between the dwellings, occupants, and environmental systems. System dynamics (SD) was used as both the methodology and tool to identify and capture the 'cause and effect' of different variables and parameters influencing OTC as well as quantitatively simulate its behaviour. The results showed a population of outcomes to include dwelling heat gains, heat losses, perceived dwelling temperature, occupants' metabolic build-up, and occupants comfort trends. The sensitivity analysis of some of the parameters in the model revealed that there is no plausible or erratic behaviour in the output of the occupants' comfort when subjected to dwelling temperature set-point and insulation factor parameters. The study concluded that the new SD tool has the capability of being used as a learning laboratory to experiment changes in OTC in the face of rapidly changing climate.

Keywords: Dwelling, energy, thermal comfort, system dynamics

INTRODUCTION

The housing sector in the UK is one of the highest consumer of energy with about 26% of the total carbon emissions (Macleay *et al.*, 2009). This has then seen the domestic sector of the UK economy as focus for both mitigation and adaptation agendas in order that carbon emissions reductions target of 80% by 2050 based on 1990 levels as laid down by the Climate Change Act of 2008 is achieved. As such, sustainability agenda has been in the forefront of decision makers because of the effects of climate change (Georgiadu, Hacking & Guthrie, 2012; Anisimova, 2011). Undoubtedly, the climate change effects have shaped the way people live. According to Nicol (2007), this has led to an increase in the cost of living or what could be termed as a reduction in the standard of living of some, while the overall health of others has been badly affected due to fuel poverty. This is evidenced in the fact that occupants of dwellings are striving hard to get their energy consumption reduced. Evidently, this has direct effect on the thermal comfort standards of occupants of those dwellings.

In temperate regions like the UK, about 90% of the time is spent indoors. Indoor thermal comfort of occupants is seen as a key component of studies relating to energy consumption and carbon emissions in dwellings. In the UK, meeting the legally binding target of carbon emissions reduction, a number of policies/strategies have been initiated by the decision makers. For example; fabric insulation improvement, energy tariffs, initiatives on fuel poverty, amongst others. These policy initiatives have influence on how occupants respond, especially in terms of occupants' thermal comfort (OTC). Predicting occupants' response to these policy initiatives in terms of OTC is an important research agenda that has the capability of contributing vastly to energy studies.

Indoor thermal comfort can be predicted with the use of a number of environmental parameters like temperature, humidity and many other parameters. Previous research efforts involving OTC have immensely benefitted from building physics and numerical simulation models, which are purely quantitative. However, the research paradigm within this enclave is changing by accommodating the qualitative issues in modelling OTC in dwellings. This study, therefore, used the system dynamics (SD) approach to model the OTC by considering the intrinsic interrelationship between the dwellings, occupants, and environmental systems. The system dynamics approach was used to identify and capture the "cause and effect" of different variables and parameters (both qualitative and quantitative) influencing OTC and quantitatively simulate its behaviour.

RESEARCH METHODS

The methodology for this study is based on the system dynamics approach as captured in Figure 1 based on Ranganath and Rodrigues (2008). The approach is hinged on the pragmatist research paradigm involving triangulation of different research strategies including quantitative and qualitative research strategies. The methodology firmed up for the study (Figure 1) indicates that the first step identified the problem in question and properly articulate it through the situation analysis. This involves identifying the variables in the problem and relates them to one another in order to find out the causal relationships and feedbacks in the system. At this stage, the time-based policy parameters, which influence the dynamics of the system under study were identified as well.

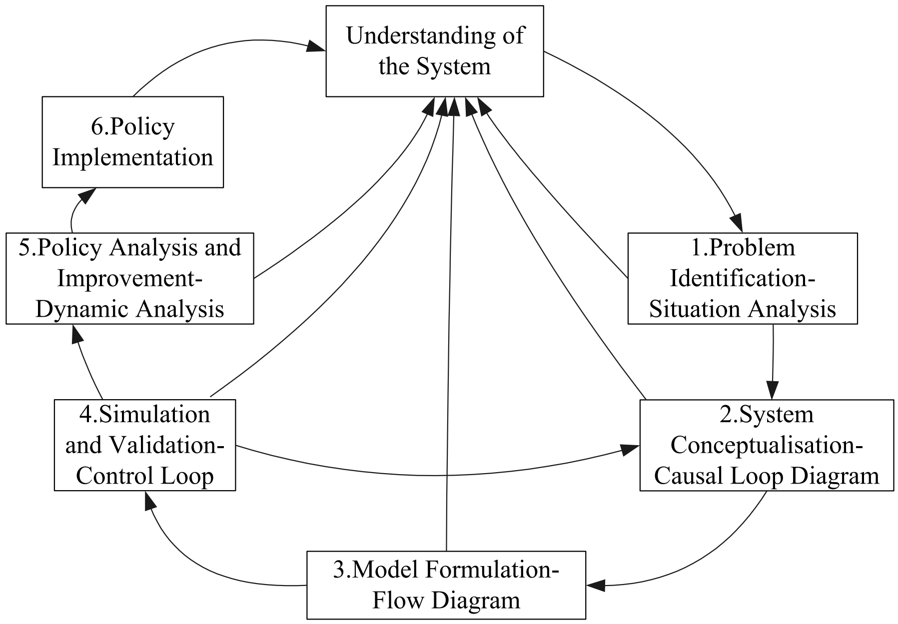

Figure1. System dynamics approach (Ranganath and Rodrigues, 2008)

The second step conceptualised the OTC system by representing the identified variables in terms of "cause and effect" relationship pictorially called the Causal Loop Diagram (CLD). This will show the interdependencies of the variables that show diagrammatically the complexity involved. An example of a CLD is shown in Figure 2. The output from the second step of the approach was transformed into what is called the Stock and Flow Diagram (SFD) as a way of formulating the OTC system. The SFDs are the pictorial representation of the behaviour of the system in the form of accumulation (stock) and flow (rate). Here, the variables are related together mathematically in form of equations. The equations may be generated numerically and/or qualitatively based on experts' experience of the problem. Having done this, the third step automatically led to the fourth step where the SFD was turned into a simulation model. It must be emphasized that mere CLD or SFD do not constitute the system dynamics. It is when the variables in the model are related together in terms of equations before it can be said that it forms the simulation model. The model was validated accordingly and the simulation was then run. The output of the simulation was presented in the form of graphs. These graphs reveal the pattern exhibit by the variables under study over a period of time. These outputs can make informed policy analysis and improvement to be carried out (Step five) and eventually, the policy implementation, which is the last step of the approach.

SYSTEM CONCEPTUALISATION AND FORMULATION

The thermal comfort of occupants was conceptualised using the interaction of the occupants with the dwelling internal heat as shown in Figure 2. The CLD was used to depict the kind of thermodynamics existing in the interaction based on building physics. For example, the conceptual model gives the causal structure of the variables hypothesised to be driving the dwelling internal heat – occupants thermal comfort relationship. Within the dwelling internal heat system, the CLD in Figure 2 indicates that the dwelling internal heat is being driven by a combination of natural and artificial heat transfers and dwelling heat gains. A change in the internal and external temperatures within the dwelling creates a temperature gap which are fluctuating around the set-point temperature as provided by the occupants. It is important to make clear that within the dwelling system, temperature set-point and dwelling internal temperature modulate the artificial heat transfer and this in turn moderates the dwelling internal heat. Accordingly, Figure 2 also indicates that dwelling heat gains are aggregated from many sources. These sources include those from solar gains, artificial lighting, cooking, water usage, appliances use, and the number of people in the dwelling. However, the lack of proper airtightness within the dwelling may result in infiltrations, which may therefore cause heat losses from the dwelling and consequently reduce the dwelling heat gains.

In terms of occupants' comfort, CIBSE (2006) divides thermal environment of occupants in dwellings into three broad categories to include thermal comfort, thermal, discomfort, and thermal stress. Based on the International Standard Organisation (ISO) 7730 (ISO, 1994), the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) (ASHRAE, 2004), and CIBSE (2006), thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment". That is, the condition when someone is not feeling either too hot or too cold. Thermal discomfort, however, expresses the condition when people start to feel uncomfortable, but without any unwell conditions (CIBSE, 2006). Similarly, thermal stress gives uncomfortable conditions to occupants which have the potential of causing harmful medical conditions.

The occupants' thermal environment is not straight forward and cannot be expressed in degrees nor can it be satisfactorily defined by acceptable temperature ranges. This is a personal experience dependent on a great number of variables, which is likely to be different from person to person within the same space. These variables can be (1) environmental – air temperature, relative humidity, air velocity, radiant temperature; (2) personal – clothing, metabolic heat; (3) other contributing variables – access to food and drink, acclimatisation, state of health. The positive feedback loop (upper part of Figure 2) indicates that the dwelling internal heat will continue to increase or decline, while the negative feedback loop sets out to stabilise and balance the system over time based on the effect of artificial heat transfer in dwelling.

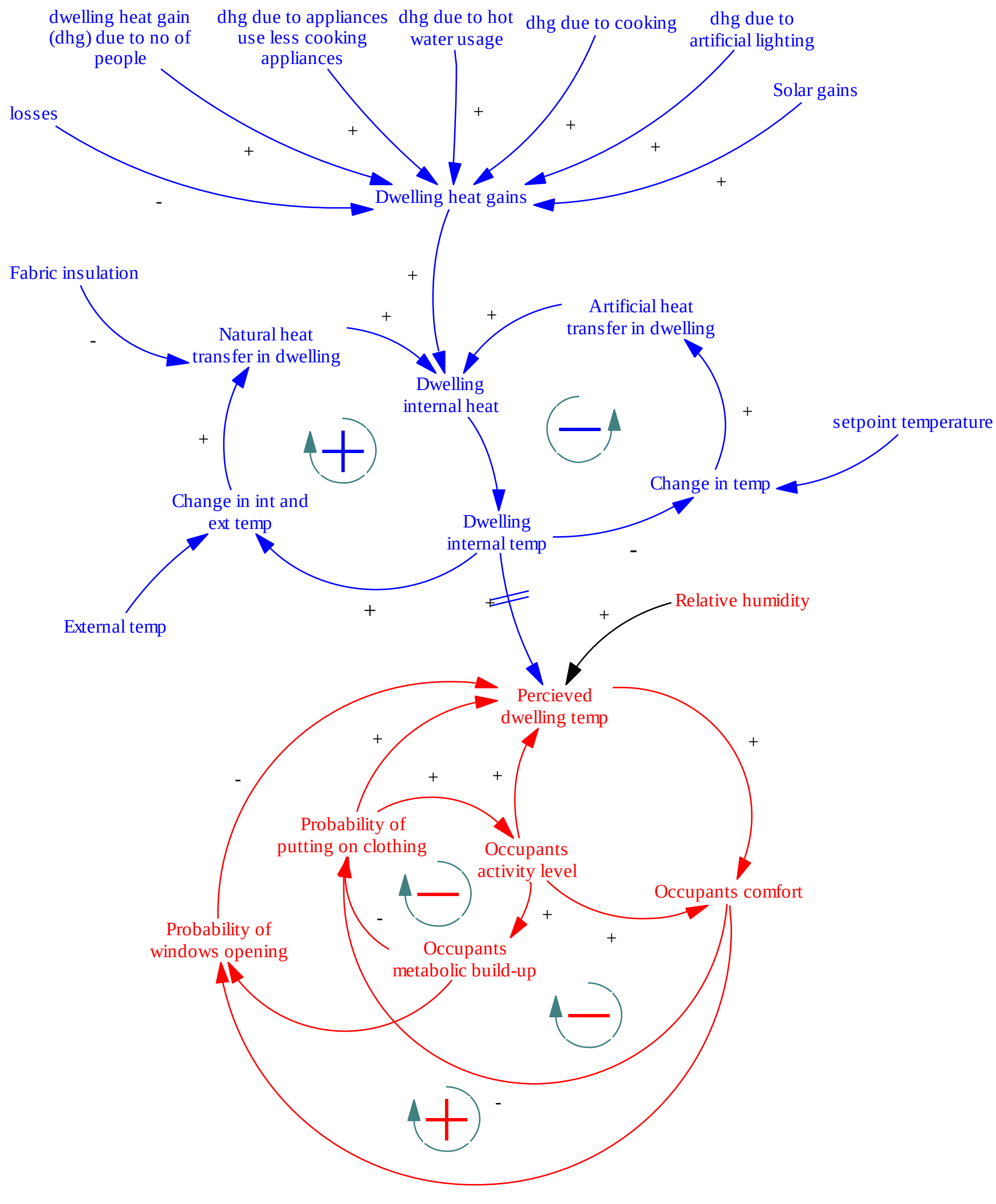

Figure 2. CLD for dwelling internal heat – occupants comfort interaction

The second part of Figure 2 indicates the CLD about the occupants' thermal comfort. In this part, a causal model of different variables hypothesised to affect occupants' thermal comfort herein refers as occupants' comfort was presented. It was postulated that the major variables that drive occupants' comfort here are "occupants' activity level" and "perceived dwelling temperature". It needs to mention that "perceived dwelling temperature" is at the heart of this causal model with five different inflows from "relative humidity", "dwelling internal temperature", "occupants' activity level", "probability of putting on clothing", and "probability of windows opening". All these variables are interrelated in a non–linear way and work seamlessly together.

For the lower part of Figure 2, a total of three different feedback loops (with two negative and a positive feedback loops) were constructed. The first balancing feedback loop involves [occupants' comfort – probability of putting on clothing – perceived dwelling temperature], while the second one takes the following variables [occupants' activity level – occupants metabolic build-up – probability of putting on clothing]. Additionally, the reinforcing loop involves [occupants' comfort – probability of windows opening – perceived dwelling temperature]. The behaviour of the model is expected to be predominately dictated by the multi-loops within the CLD. The CLD were then transformed into the SFD. However, the SFD for the model is not presented here due space constraint.

SIMULATION RESULTS

The results of the simulation regarding the behaviour of some key variables for OTC model is hereunder presented. Modelling the dwelling internal heat is required in order to see its effects on occupants' thermal comfort. The dwelling internal heat is principally influenced by the amount of heat gained into the dwelling and determines the dwelling internal temperature as discussed in the preceding sections. The total dwelling heat gains (DHGs) was modelled from six different sources as explained under the system conceptualisation and formulation section to include: DHGs due to appliances, artificial lighting, cooking, number of people (metabolic heat gains), water heating, and solar gains. The degree of infiltration into/out of the dwelling is modelled and captured as heat losses. Figure 3 shows the model behaviour for DHGs due to appliances, artificial lighting, cooking, water heating, heat losses, and number of people. The behaviour exhibit reveals that the DHGs due to appliances, artificial lighting, cooking, number of people, and water heating follow the same trajectory patterns of gentle decline.

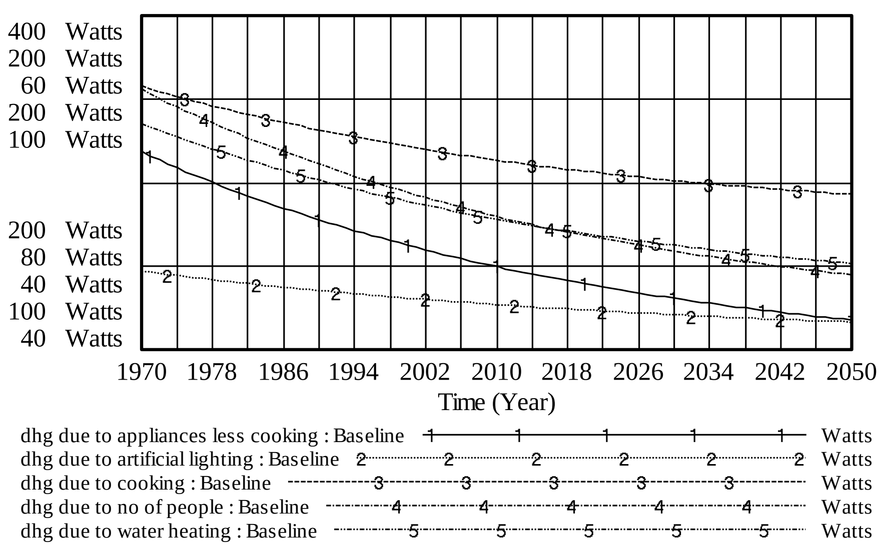

Figure 3. Model behaviour of dwelling heat gains

Further to these, the result as shown in Figure 4 gives an insight into the pattern of behaviour expecting from the heat losses from the dwellings. The output suggests that heat losses from dwellings would decrease over time. This may be as a result of different schemes put in place at improving airtightness in dwellings based on melioration of fabric insulation of dwellings.

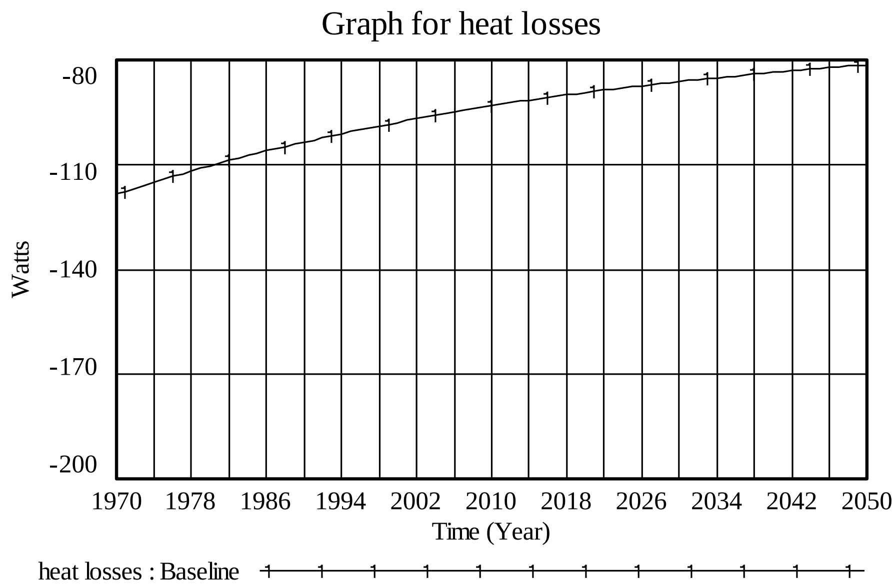

Figure 4. Model behaviour of dwelling heat losses

The behaviour of key variables for occupants' thermal comfort part of the model is presented and insights generated from the behaviour are discussed as well. The average dwelling internal temperature from the preceding section in combination with the average relative humidity serves as input to the model. This is mainly to model the perceived dwelling temperature in a bid to model occupants' comfort. The pattern exhibited by the perceived dwelling temperature variable (Figure 5) follows a gentle growth. As the value of perceived dwelling temperature increases, this will trigger actions from the occupants. The actions assumed and included in the model are either to open window(s) or put on more clothing with high thermal resistance as the case may be in order to get the required comfort level.

Stemming from the above, the output of the model as shown in Figures 6and 7 suggest that the pattern of behaviour of occupants' metabolic build-up and occupants comfort grow over time. It is as a result of rise in perceived dwelling temperature which may lead to a decline in the quest for more space heating and hot water usage. It needs to mention that there will be a time when these growths would reach a saturation level at which time, they tend to decline. Though, this model produces no such plausible insight, may be due to the fact that occupants comfort is being regulated by the two aforementioned actions of the occupants – window opening and putting on of clothing. It is also possible that artificial ventilation may be introduced in future should the value of occupants' comfort outrageously increased in such a way that the two aforesaid actions of the occupants as assumed in this model no longer validly hold.

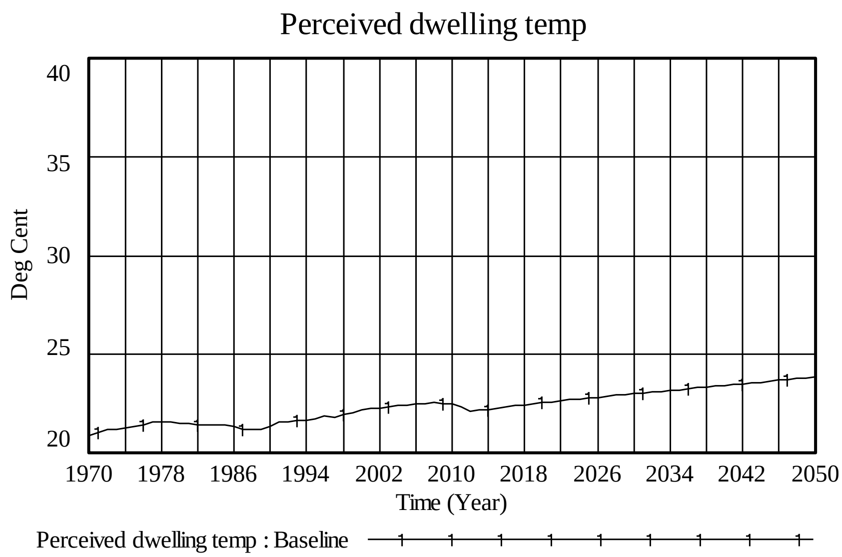

Figure 5. Model behaviour of perceived dwelling temperature

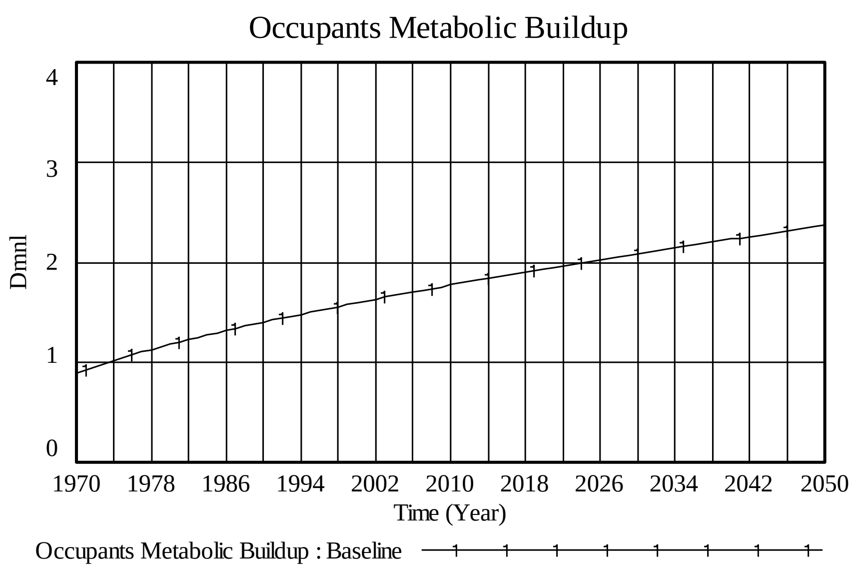

Figure 6. Model behaviour of occupants' metabolic build-up

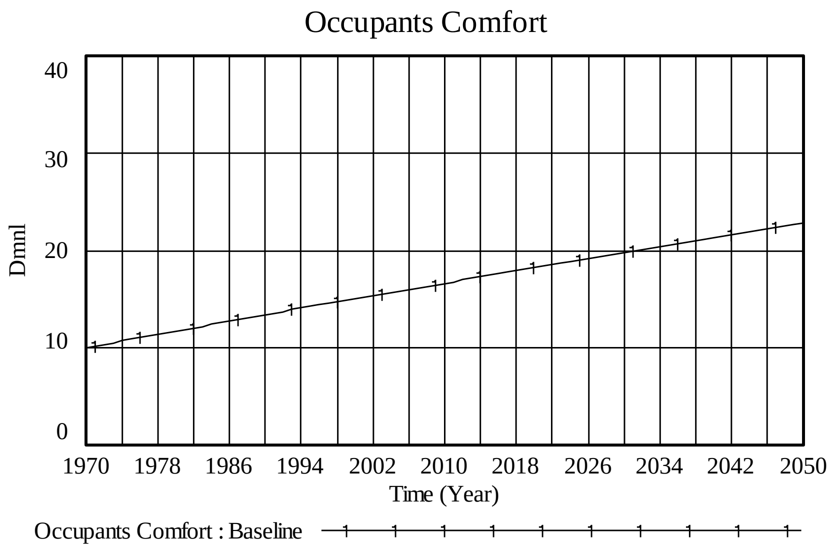

Figure 7. Model behaviour of occupants' comfort

SENSITIVITY ANALYSIS

In system dynamics models, sensitivity analysis is performed to test the robustness of the model by ensuring that uncertainties and estimating errors do not significantly affect the overall behaviour of the model. In order to check the ability of the OTC model's ability to adjust to parameter changes, sensitivity analysis was therefore used to assess the behaviour of "occupants comfort" variable. The study made use of numerical sensitivity analysis by changing some parameters in the models such as policy livers like set-point temperature and insulation factor. For each parameter, the numerical sensitivity test is conducted by reducing and increasing the value of the parameter round the mean value of those parameters. The uniform distribution function was used to check the sensitivity of "occupants comfort" to both set-point temperature and insulation factor. The dynamic simulation results of the OTC system are shown in Figures 8 and 9 for set-point temperature and insulation factor parameters respectively. The results suggest there is no erratic behaviour for occupants' comfort for the two parameters checked. These therefore implied confidence in the output of the model.

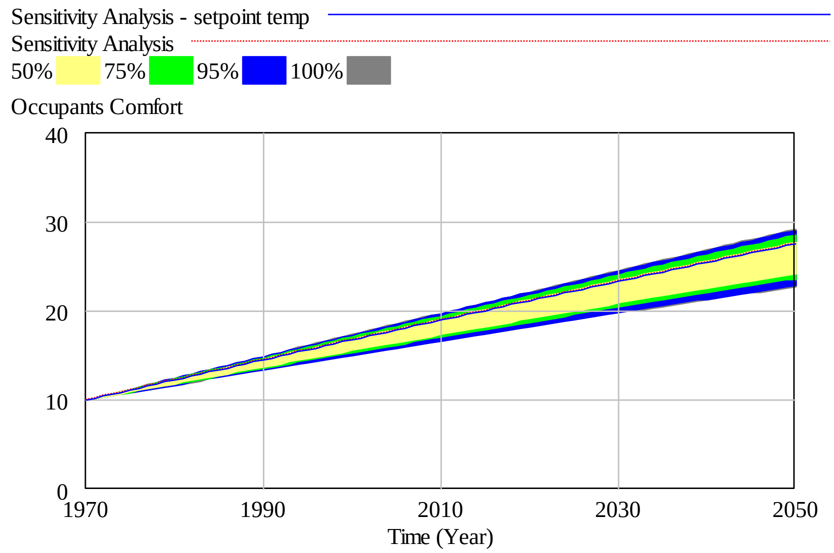

Figure 8. Model behaviour of occupants metabolic build-up

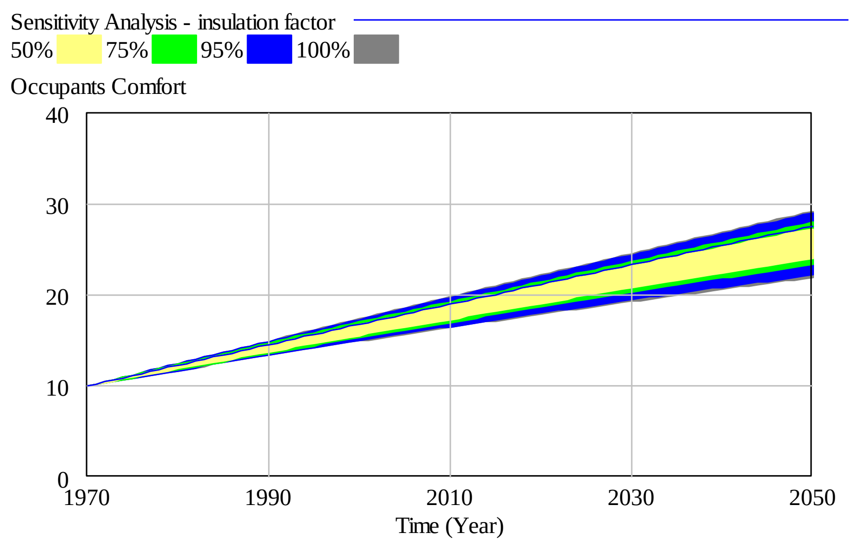

Figure 9. Model behaviour of occupants metabolic build-up

CONCLUSIONS

The research in this paper used the system dynamics approach to model and simulate occupants thermal comfort in dwellings. The paper described and discussed the model conceptualisation and formulation in terms of capturing the causal loop diagram of the variables purporting to influence occupants thermal comfort in dwellings. The paper argued that previous research efforts involving occupants' thermal comfort have immensely benefitted from building physics and numerical simulation models. However, the study in this paper advocated a shift in occupants' thermal comfort modelling paradigm to include a model based on both qualitative and quantitative data based on system dynamics approach. The findings from the simulation suggested that the profile of dwellings heat gains DHGs due to appliances, artificial lighting, cooking, number of people, and water heating will follow a gentle decline pattern over the years till 2050. However, the findings from heat losses from dwellings indicated that they would decrease over time. Additionally, the output of the model suggested that the pattern of behaviour of occupants' metabolic build-up and occupants comfort will grow over time. The sensitivity analysis of some of the parameters in the model revealed that there is no plausible or erratic behaviour in the output of the occupants' comfort when subjected to dwelling temperature set-point and insulation factor parameters. The study concluded that the new SD tool has the capability of being used as a learning laboratory to experiment changes in OTC in the face of rapidly changing climate.

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Using Fanger's Modified PMVe-PPDe Model for Thermal Comfort in Selected Students' Hostel Buildings in South-South, Nigeria

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ABSTRACT

This study evaluated the indoor thermal conditions of selected hostel buildings of a tertiary institution in the south-south region of Nigeria. The specific objectives of the study are to assess the indoor thermal conditions and determine the indoor thermal comfort using Fanger's modified percentage mean votes – percentage people dissatisfied (PMVe – PPDe) model and actual thermal sensation of occupants of the selected hostels. The study made use of a two-stage sampling approach. The first stage used the random sampling approach to select the hostels while the second stage used the stratified random sampling approach to select the sampled rooms. Data were collected from the hostels based on the use of questionnaire and on-site measurement of indoor climatic conditions with the use of a handheld microclimatic tracking device. Data were analysed using both descriptive and inferential statistics. The findings of the study indicate that for the period of the research, the indoor temperature ranged from 25.53ºC – 30.33ºC and the relative humidity ranged from 77.53% - 91.93%. Additionally, the PMVe values estimated for the study area ranged from 0.41 to 0.97 and PPDe from 8 to 20%. Furthermore, the actual thermal sensation of the occupants of the selected hostels also ranged from 0.20 to 0.81, although the actual values are different from that of PMVe values. The study concluded that the indoor thermal conditions of the hostels were observed to be comfortable as they fell within the standard thermal comfort range as in the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 55 and ISO Standard 7730.

Keywords: Hostel buildings, Nigeria, PMVe-PPDe, indoor thermal comfort, thermal sensation votes, tropical climate

INTRODUCTION

Research in the area of occupants' thermal comfort in buildings has been on for many years now. As such, many remarkable findings have evolved since, shaping thermal considerations of building fabrics. According to American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) (2010), thermal comfort is defined as a condition of the mind that expresses satisfaction with the thermal environment. Drawing from that definition, Ayoade (2008) and Ojeh (2011) express thermal comfort as a scenario when one does not desire to increase or decrease the air temperature of that area or place either because of excessive cold or heat in that environment. As a result, productivity of occupants of buildings has been linked to occupants' thermal comfort. For example, Kim, Kim and Park (2007) suggested that productivity level of occupants tends to increase by about 15% as a result of thermal satisfaction. This satisfaction can be borne out of acceptable thermal environment through the use of adaptive behaviours and obtained if certain factors are put into consideration during the design stage of the structure like; air temperature, radiant temperature, air movement, humidity, clothing adjustment, opening/closing windows, the activities to be carried out during the use of the structure, *etc.* (Abotutu & Ojeh, 2013).

In higher institutions of learning, one of the main reasons why they establish and provide hostel accommodation for their students is to ensure their comfort and enhance their academic performance. The poor dwelling condition of buildings (hostels) observed by Loomans (1998) is as a result of improper design, wrong choice of building materials and location; and these have posed a great level of threat to thermal comfort of the students living in those hostels. As such, the academic performances, intellectual capacity and the development of students can be affected by the thermal comfort (Dhaka, *et al.*, 2013; Appah-Dankyl & Koranteng, 2012). Fanger (1972) also stated that human intellectual performances and insight in general will reach its maximum potential if human beings are in a comfortable thermal condition. A thermally comfortable environment will enhance a good quality night sleep, which has been observed to play a significant role in ensuring an adequate day time functioning of students: concentration, attention and comprehension as well as an efficient learning level (Sekhar & Goh, 2011; Lin & Deng, 2006). Lack of adequate sleep due to poor thermal condition not only affects the performances and intellectual capacity but also the health of the students (occupants). The study of thermal comfort is not only concerned with the satisfaction of the occupants but also with the efficient use of energy (Ye, Zhang, Pang, & Zhao, 2006) in order to ensure sustainability in an energy deficient world.

Quite a number of studies have been conducted in Nigeria on indoor thermal environment and occupants' thermal comfort under various climatic conditions and building designs using laboratory and field studies (Olanipekun, 2012; Adunola & Ajibola, 2012; Adebamowo & Olusanya, 2012; Adunola, 2011; Adebamowo & Akande, 2010). While a few of them focus on students' hostel buildings only in the south – western region of Nigeria, there is limited evidence to support that such studies have been conducted in the south – south region of Nigeria with distinct climatic conditions greatly different from that of south – west, Nigeria. As such, it is imperative to conduct this type of research in the south – south region of Nigeria with the case study of a Federal University in the region. Certainly, there are climatic differences between the two regions. Therefore, the study aims to assess the indoor thermal conditions of the selected hostels, determine the indoor thermal comfort of the selected hostels using Fanger's modified predicted mean vote (PMVe) and percentage people dissatisfied (PPDe) model and actual thermal sensation of the students to their environment in the south – south region of Nigeria. Adaptive comfort model has been used in the tropics, however, Fanger's modified PMV-PPD by including an expectancy factor (e) has been found useful to predict thermal comfort in naturally ventilated buildings in the tropics (Olanipekun, 2014a). Hence, the justification for the approach used.

One of the profound significance of this study is to inform the design professionals in designing students' hostels that have the capacity for optimal thermal comfort of the students. This information will guide them in designing the hostels for natural ventilation, which hopefully will stimulate academic performance, intellectual capacity and development of the students. A number of hypotheses were formulated for the study as follows:

i. There is no significant variation in the means of PMVe values across the selected hostels.
ii. There is no significant variation in the means of the actual thermal sensation of the students to their environment across the selected hostels.
iii. There is no significant difference in the means of PMVe model and the actual thermal sensation of the students.

PREVIOUS STUDIES ON THERMAL COMFORT OF OCCUPANTS IN BUILDINGS

There are many studies in the area of thermal comfort in buildings, especially in the tropics. Among those studies is the work of Kwok (1998). The work examined the ASHRAE standard 55 (2013; 2010) criteria in meeting its applicability in tropical classrooms. This standard specifies the exact criteria required to meet a thermally comfortable environment. A field study was conducted through the use of survey questionnaire, interviews, physical measurements and behavioural observations. Result showed that majority of the classrooms did not meet the physical criteria of standard 55 comfort zones. Another study by Tzu-ping *et al.* (2001) on Mediterranean and subtropical climates where the two climates were compared regarding thermal sensation and the acceptable range for outdoor occupants. The research used both physical measurements and questionnaire survey. The results of the study revealed that there exist a significant difference between both climatic regions.

In Warri, Nigeria; Abotutu and Ojeh (2013) conducted a research on thermal comfort of occupants in relation to the dwelling structural properties of buildings. The design approach adopted a field study survey where the primary data (climatic conditions) were observed and recorded for four months while a six-year (2005-2010) secondary data were obtained from Warri meteorological agency. The structural property was based on the window type used by the occupants in the dwelling. The data was analysed using one way ANOVA and the pair t-test. Result showed that occupants with the wooden windows were more thermally comfortable compared to occupants with sliding window in the absence of artificial ventilation. The study of Malgwi and Musa (2014) assessed the thermal comfort of urban entertainment centres during the hot-dry climatic conditions in Nigeria, through the evaluation of the effect of environmental design parameters. It was discovered that most of the buildings in the hot dry climatic area were not evaluated properly at the design stage against the environment conditions of the place as most of the buildings solely on mechanical means of cooling to solve overheating. The temperature and humidity of the rooms were measured and recorded for a space of three months. The result revealed that the comfort range was below the ASHRAE standard 55 provisions for temperature.

Research conducted by Olanipekun (2014b) on non- air - conditioned students' hostel building investigating the applicability of PMV- PPD model. Data obtained from physical measurement, questionnaire survey and observations were analysed. The environmental variables measured fell below the comfort range recommended by ASSHRAE 55 and ISO 7730 standards. Result showed that 85% of the calculated PMV values fell within the comfort range recommended by ASHRAE standard 55 and ISO 7730 standard. The obtained PPD results showed only a slight overestimation of 8.9% of the percentage dissatisfied under neutrality. The study, however recommended the use of adaptive comfort model in predicting indoor climatic conditions under steady-state non-uniform environments. In yet another study by Olanipekun (2014c), his research was in the area of students' accommodation in the south-western part of Nigeria. The study used PMV-PPD model and field survey to evaluate the thermal comfort in a naturally ventilated hostel. The study used a field survey and secondary data from meteorological centre for the research. The results showed a lack of correlation between the calculated PMV index and acceptable range defined by ISO 7730 standard. Further, there was no relationship between the thermal conditions predicted by PMV-PPD values and actual thermal comfort votes. The study concluded that the Fanger`s PMV-PPD model cannot be used to predict the quality of indoor climate in the selected naturally ventilated hostel building as it overestimated occupants' comfort and dissatisfaction levels. Furthermore, Olanipekun (2014a) argued that in order to make PMV-PPD model applicable in non-air-conditioned buildings, the use of Fanger's proposed PMVe-PPDe model can prove useful by including an expectancy factor (e). The study used the approach and concluded that PMVe-PPDe is effective in non-air-conditioned buildings in tropical climates.

Beyond the shores of tropical climates, numerous studies have been conducted on occupants' thermal comfort in buildings. Among the studies are that of Kasper and Toftum (2007); Stefano; Roberta and Macro (2009), Ioannou and Itard (2014); and Natarajan, Rodriguez and Vellei (2015). The results of these studies are profound and illuminating.

METHODOLOGY

Study Area

The field study focused on selected undergraduate hostels at the University of Uyo, Uyo, in Akwa Ibom State, Nigeria. Akwa Ibom State is situated in the tropical area of South –

South, Nigeria as shown in Figure 1. It lies between the latitude $4°32' and\ 5°53'$ North and longitude $7°25' and\ 8°25'$ East. It has a warm humid climate characterized by two seasons (rain and dry). The raining season is usually between the months of April and October, whereas the dry season is between the months of November and March. The study area has a diurnal temperature range of minimum $25.0℃\ to\ 25.9\ ℃$ and a maximum $25.9℃\ to\ 26.8℃$ with a mean annual relative humidity value of 90.08%. The hostel buildings of the university are bungalow buildings of about three (3) meters high, with aluminium roofing sheets. The walls are made of 225mm aerated hollow sandcrete block, rendered with cream paint outside and with an alteration of pink and cream coloured paint inside. The hostels under consideration varied in dimensions, design and locations. The first one named 'Hall 4' is an almost square shaped structure of 53.9m by 54.1m complete with a courtyard of 31.2m by 33.7m. It has a total of thirty (30) rooms and made of screed flooring. 'Hall 3b' has a similar structure with 'Hall 4' except for the dimension which is 37.55m by 47.5m. It has a courtyard of 17.6m by 30.4m and made up of a total of thirty (30) rooms as well. The rooms are finished with floor tiles. 'Halls 6A and 6B' have the same dimensions of 14.40m by120.03m, with a total of sixty (60) rooms each. An example of the hostels is shown in Figure 2.

Figure 1. A Map Showing Uyo, Akwa Ibom State, Nigeria

Figure 2. Front View of Hall 4

Research Design and Sampling Approach

The research design is more of a case study design which applies both an objective and subjective approach in deriving its' data. Descriptive research was also considered necessary due to the relation of the variables. The population of the study is on the selected students' hostels in both the annex and main campus of the University of Uyo, Uyo, South-South, Nigeria, which are operated by the institution. The study made use of a two-stage sampling approach. The first stage had to do with the random sampling of four (4) hostels out of eight (8) hostels, where one of the female hostels was under reconstruction which was automatically off the list for selection. The four (4) hostels which were randomly chosen for this study were based on their differences in design, materials used for construction, location, etc.

The second stage of the selection had to do with the sample selection of various rooms from each hostel due to the size and strategic position of the room and numbers of occupants in the rooms, these was done based on stratified random sampling. On the long run occupants of this selected room were require to fill the questionnaires, it was limited to only their rooms in other to ascertain their personal thermal sensation judgment on their specific rooms.

Data Collection

Data was collected through objective and subjective approaches; which will help in the balancing of the strength and weakness inherent in the individual data collection and the data gotten from the metrological station for the outdoor thermal condition, strategies used helped in determining if the hostel is thermally comfortable in relation to the outdoor climatic conditions.

Objective Approach: The indoor thermal environment was captured by measuring the physical thermal parameters. This was achieved with use of a handheld weather tracker (Kestrel 4500) for four months (July – October, 2015). Specifically, indoor temperature, relative humidity and wind speed were all captured using the instrument. In order to obtain the maximum effectiveness of the weather tracker, the instrument was placed 1.1metres above the ground level and it was read between the hours of 8a.m and 6p.m on an hourly basis. This is basically to capture different rapidly changing environmental conditions throughout the day. The outdoor environmental data were collected from a nearby local meteorological station for all the dates that the indoor environmental data were collected. The data collected from this meteorological station include air temperature, relative humidity, air velocity and solar radiations. Other parameters like clothing insulation and occupants' metabolic rate were estimated based on the approach discussed in next subsection. Microsoft Excel template was then created to calculate the value of PMVe for each data point. PPDe values were thereafter computed based on the values of PMVe.

Subjective Approach: This approach aimed at finding out the occupants' perception of their thermal sensation to their environment and to capture data regarding the clothing they put on and activities performed an hour prior to the survey. Questionnaire was used to investigate the thermal perception of occupants asking about their thermal sensation to their environment using the ASHRAE thermal sensation scale as shown in Table 1. Among the general questions posed to the respondents include requiring them to tick what they wear by means of cloth check-list, in order to find out the actual clothing level. For each data point, the clothing was converted into *clo* based on the average value of all clothing indicated using the standard provided by ISO9920 (2009). Additionally, using the tables provided in ISO7730 (2005) and ASHRAE 55 (2013), the activity levels of each respondent an hour before the survey were captured and converted to *met* units. The average *met* value for each data point was then calculated.

Table 1. Thermal Scale

PMV	-3	-2	-1	0	1	2	3
Thermal Sensation	Cold	Cool	Slightly Cold	Neutral	Slightly Warm	Warm	Hot

Method of Data Analysis

Descriptive analysis of data captured were performed. For example, mean and standard deviation were computed for the indoor climatic conditions. Hypotheses were also tested using analysis of variance (ANOVA) approach to test hypothesis one and two, while hypothesis three was tested using paired sample T- test.

DATA ANALYSIS AND DISCUSSION OF FINDINGS

Indoor Climatic Conditions

From the reading observed on specific days in various hostels for the sampled rooms four months, it was observed that in the month of July the temperature ranged from 25.58^{o}c - 29.76^{o}c (mean = 27.32, Std deviation = 1.71), the relative humidity ranged from 76.80 % - 91.41 % (mean = 84.18, Std deviation =5.99). For the month of August, the temperature ranged between 26.70^{o}c - 29.55^{o}c (mean = 28.10, Std deviation = 1.02) with a relative humidity ranging between 81.22% - 90.38% (mean = 85.85, Std deviation = 3.65). In the month of September, the temperature ranging between 27.06^{o}c – 29.52^{o}c (mean = 27.96, Std deviation =0.97) while the relative humidity was between 80.57% - 92.00% (mean =86.61, Std deviation =4.70). Finally, in the month of October the temperature ranged between 27.33^{o}c - 30.33^{o}c (mean = 28.67, Std deviation = 1.27) while the relative humidity ranged from 74.33% - 85.80 % 9 (mean = 79.67, Std deviation = 4.62062). Tables 2 and 3 show the descriptive statistics of indoor temperature and relative humidity data captured.

Table 2. Indoor Temperature

	Minimum	Maximum	Mean	Standard Deviation
Month of July				
Hall 4	25.57	26.91	26.0767	0.72728
Hall 3B	25.53	28.99	26.9567	1.80802
Hall 6A	26.11	29.76	27.5067	1.97003
Hall 6B	26.61	29.11	27.5733	1.34500
Month of August				
Hall 4	26.70	28.39	27.5100	0.84717
Hall 3B	27.36	28.78	28.0200	0.71526
Hall 6A	27.27	29.20	27.9267	1.10292
Hall 6B	27.51	29.55	28.1133	0.95970
Month of September				
Hall 4	27.13	27.90	27.4500	0.40112
Hall 3B	27.23	28.52	27.6967	0.71515
Hall 6A	27.06	29.52	27.9633	1.35390
Hall 6B	27.25	29.10	27.9433	1.00828
Month of October				
Hall 4	27.36	29.05	28.4800	0.97000
Hall 3B	27.76	29.88	28.7233	1.07314
Hall 6A	27.33	30.33	29.0400	1.54347
Hall 6B	27.69	29.94	28.7933	1.12563

Table 3. Indoor Relative Humidity

	Minimum	Maximum	Mean	Standard Deviation
Month of July				
Hall 4	83.55	89.40	86.3167	2.93783
Hall 3B	77.53	90.73	84.0200	6.60275
Hall 6A	76.80	91.41	85.0900	7.49869
Hall 6B	78.80	85.27	82.7133	3.44175
Month of August				
Hall 4	85.21	90.38	88.4167	2.80029
Hall 3B	81.22	87.20	84.4133	3.01067
Hall 6A	82.39	89.67	87.1567	4.13010
Hall 6B	82.05	88.69	86.3300	3.71311
Month of September				
Hall 4	86.11	91.93	88.9533	2.91229
Hall 3B	81.90	88.33	85.6633	3.35235
Hall 6A	81.86	92.00	88.1900	5.51976
Hall 6B	80.57	90.19	86.4433	5.15055
Month of October				
Hall 4	77.90	81.95	79.7000	2.06216

Hall 3B	74.33	81.40	78.4667	3.68541
Hall 6A	74.47	85.80	79.3133	5.84103
Hall 6B	76.07	85.33	80.6900	4.63003

PMVe – PPDe Analysis for the Halls

The PMVe and PPDe were determined based on the approach discussed in the methodology section. From the calculation as shown in Table 4, it was observed that the PMV values range from 0.41 to 0.97 indicating that the occupants were slightly cool. Also, Table 5 indicates that for the period of the study, the PPDe values range from 8% to 20%, which by implication means that the students are satisfied with the thermal comfort of their respective rooms.

Table 4. PMVe Calculated Results

Hostels	July	August	September	October
Hall 4	0.92	0.81	0.73	0.61
Hall 3B	0.86	0.74	0.62	0.54
Hall 6A	0.86	0.80	0.60	0.41
Hall 6B	0.97	0.83	0.88	0.62
Average	0.90	0.80	0.71	0.54

Table 5. PPDe Calculated Results

Hostels	July	August	September	October
Hall 4	16	16	8.3	8.3
Hall 3B	8	16	8.3	8.3
Hall 6A	20	8	20	8
Hall 6B	12.5	12.5	12.5	12.5
Average	14.13	11.13	12.28	7.28

Actual Thermal Sensation Votes

Occupants of each room were required to give their thermal feelings on the thermal sensation scale printed in order to indicate how they felt on several different occasions during the course of the study. This was to ascertain how they felt at that moment of the day in various different climatic conditions. The results obtained are shown in Table 6. The results indicate that the values of the actual thermal sensation of the occupants range from 0.20 to 0.81 meaning that majority of the occupants are thermally comfortable in all the hostels for all the months during the course of the study. This is may be as a result of the change in climatic condition at the time of study.

Table 6. Actual Thermal Sensation

Hostels	July	August	September	October
Hall 4	0.81	0.68	0.63	0.50
Hall 3B	0.74	0.57	0.54	0.33
Hall 6A	0.72	0.61	0.51	0.20

Hall 6B	0.84	0.67	0.67	0.50
Average	0.78	0.63	0.59	0.38

Test of the Hypotheses

To achieve the objectives of this paper, a number of hypotheses were formulated. These are discussed in the following sub-sections.

Hypothesis One (1): There is the need to test whether or not there is variation in the values of PMV computed for each of the halls. To this end, the following hypothesis is therefore formulated as follows:

H_o *= There is no significant variation in the means of PMVe values across the selected hostels.*

H_1 *= There is significant variation in the means of PMVe values across the selected hostels.*

One-way analysis of variances (ANOVA) was used to test the hypothesis. Table 7 gives the descriptive statistics for all the halls regarding the PMVe. These descriptive statistics includes the mean, Std. Deviation, 95% confidences interval for both lower and upper boundary, *etc*. for each hall.

Table 7. Descriptive Statistics of ANOVA for PMVe

	N	Mean	Std Deviation	Std. Error	95% confidences interval for mean		Minimum	Maximum
					Lower Boundary	Upper Boundary		
Hall 4	4	.7675	.13074	.06537	.5595	.9755	.61	.92
Hall 3A	4	.6900	.14000	.07000	.4672	.9128	.54	.86
Hall 6A	4	.6675	.20451	.10226	.3421	.9928	.41	.86
Hall 6B	4	.8250	.14844	.07422	.5888	1.0612	.62	.97
Total	16	.7375	.15588	.03897	.6544	.8206	.41	.97

Additionally, Table 8 shows the result of Levene’s test for homogeneity of variances tests. The reason for this test was to know whether or not the assumption of homogeneity is violated. The condition is that if the significance (sig.) value of Levene’s statistical value is greater than 0.05, then there is no violation of the assumption of homogeneity of variances otherwise, it is violated. In this study the Significance value is greater than 0.05 as shown in Table 8. Therefore, it is concluded that there was no violation of the assumptions of homogeneity.

Table 8. Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Actual Sensation	.358	3	12	.785

Table 9 shows the test statistics of the ANOVA performed. The Table gives information for both between the groups and within-groups sums of squares, degree of freedom etc. but the interest is the significance value. If the significance value is less than or equal to .05, then H_o is rejected and a Post Hoc Test has to be conducted. In the case of the result of this study, the significance value is 0.501, which is greater than 0.05. Therefore, there is no significant variation in the means of PMVe values across the selected hostels.

Table 9. Analysis of Variances (ANOVA) for PMVe

		Sum of Squares	df	Mean Square	F	Sig.
PMV	Between Groups	.063	3	.021	.833	.501
	Within Groups	.302	12	.025		
	Total	.365	15			

Hypothesis Two (2): As before, another hypothesis was tested to check whether or not there is variation in the means of the actual thermal sensation values across the selected hostels. The one-way analysis of variance (ANOVA) was used as well. Table 10 shows the descriptive statistics for the analysis.

Table 10. Descriptive Statistics of ANOVA for Actual Thermal Sensation

	N	Mean	Std Deviation	Std. Error	95% confidences interval for mean		Minimum	Maximum
					Lower Boundary	Upper Boundary		
Hall 4	4	.6550	.12819	.06410	.4510	.8590	.50	.81
Hall 3A	4	.5450	.16823	.08411	.2773	.8127	.33	.74
Hall 6A	4	.5100	.22376	.11188	.1540	.8660	.20	.72
Hall 6B	4	.6700	.13880	.06940	.4491	.8909	.50	.84
Total	16	.5950	.16693	.04173	.5060	.6840	.20	.84

As done under Section 4.4.1, Table 11 shows the result of Levene's test for homogeneity of variance test. The result indicates that there is no violation of the assumption of homogeneity.

Table 11. Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Actual Sensation	.358	3	12	.785

In order to conclude the hypothesis testing, Table 12 shows the result of ANOVA performed. Again, the result indicates that there is no significant variation in the means of actual thermal sensation values across the selected hostels.

Table 12. ANOVA for Actual Thermal Sensation

		Sum of Squares	df	Mean Square	F	Sig.
Actual Thermal Sensation	Between Groups	.076	3	.025	.886	.476
	Within Groups	.342	12	.029		
	Total	.418	15			

Hypothesis Three (3): This hypothesis tests whether or not there is significant difference in the means of PMVe model and the actual thermal sensation of the students. For this test, a box plot analysis (Figure 3) was first performed in order to have a pictorial view of the results. After, a paired sample t-test was performed. Table 13 gives the result of the paired t-test. The decision has to be taken in order to conclude whether or not there is significance difference between the two models. The significance value (*sig. = .000*) in Table 13 suggests that there is significant difference in the means of PMVe-PPDe model and the actual thermal sensation of the students. This is further supported by Figure 2. This by implication means that the null hypothesis is rejected, while the alternate hypothesis is accepted.

Table 13. Paired Sample T - Test

	N	Correlation	t	Df	Sig.(2-tailed)
Actual sensation and PMVe	16	.965	12.986	15	.000

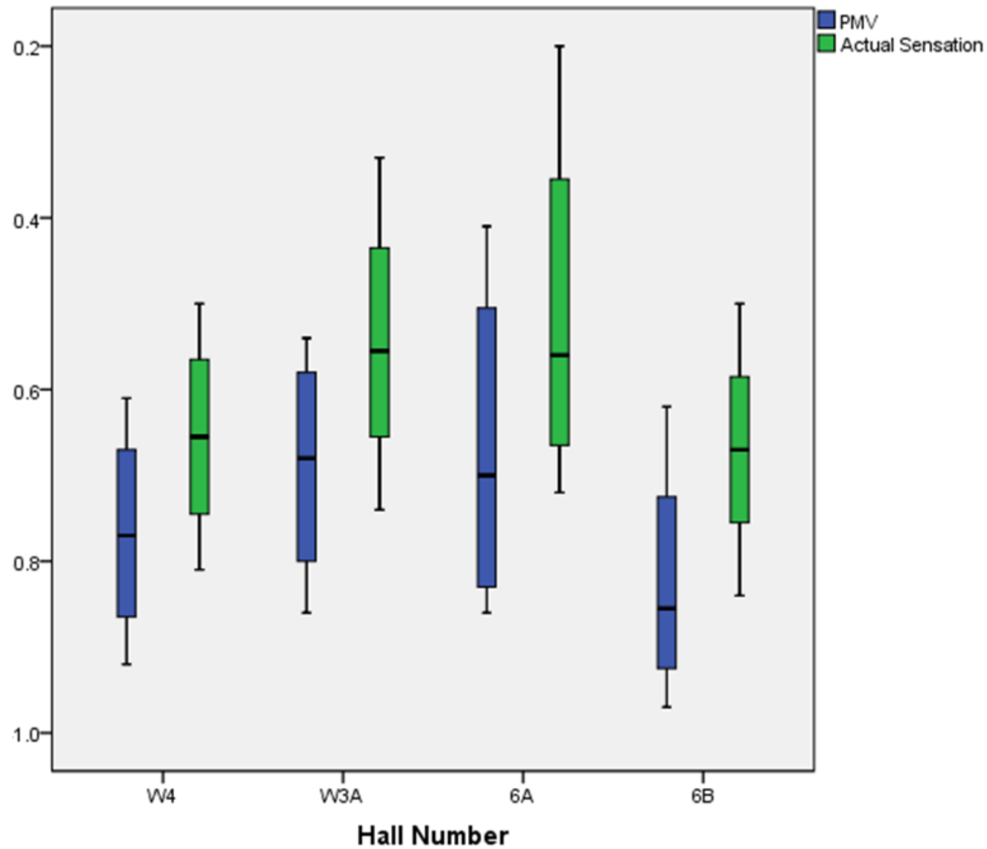

Figure 3. Box plot of PMVe and actual sensation values of students in the study area

Discussion of Findings

The findings of this research suggest that the PMVe values range from 0.41 to 0.97 and that of PPDe values range from 8% to 20%. These by implication means that the occupants were comfortable, but tending being slightly warm. However, the students are satisfied with the thermal comfort of their environment. These findings indicate that the PMVe values fell within the comfort range as provided in ASHRAE 55 and ISO 7730 standards. The finding is in agreement with the work of Olanipekun (2014b) and Olanipekun (2014c) where majority of PMV values estimated for a hostel building in south-western Nigeria was found to fell within the comfort range recommended by ASHRAE standard 55 (2013) and ISO 7730 standard (2005). Additionally, the findings indicate that the values of the actual thermal sensation of the occupants range from 0.20 to 0.81 meaning that majority of the occupants are also thermally comfortable in all the hostels for the period during the course of the study. This also suggests that the thermal sensation votes fell within the comfort range as provided in ASHRAE 55 standard (2013). This is in conformity with the research of Natarajan *et al.* (2015) regarding the use of ASHRAE 55 standard (2013) and EN Standard 15251 (2007) for non-air-conditioned buildings. In comparing of the PMVe –PPDe values with the actual thermal sensation results, it was observed that there is significant difference in the means of PMVe-PPDe model and the actual thermal sensation votes results. This difference may be due to the fact PMVe-PPDe model was unable to accurately capture the thermal comfort votes of non-air-conditioned buildings (as the case is in this study) as suggested by many studies like that of Olanipekun (2014a).

CONCLUSIONS AND RESEARCH IMPLICATIONS

The study evaluated indoor thermal conditions of selected hostels in a tertiary in institution in south-south, Nigeria. The findings suggest that the values of PMVe range from 0.41 to 0.97 for the period under study. Also, the PPDe values vary from 8% to 20%, which by implication means that the students are satisfied with the thermal comfort of their environment to a larger extent. The hypothesis tested indicates that there is no significant variation in the means of PMVe values across the selected hostels. Additionally, the findings indicate that the values of the actual thermal sensation of the occupants ranged from 0.20 to 0.81 meaning that majority of the occupants are thermally comfortable in all the selected hostels for all the months during the course of the study. The hypothesis tested suggests that there is no significant variation in the means of the actual thermal sensation of the students to their environment across the selected hostels. Also, the finding of another hypothesis tested shows that there is significant difference in the means of PMVe model and the actual thermal sensation of the students.

There are quite a number of conclusions that can be drawn from the findings of this study. Firstly, it can be concluded that the indoor thermal conditions of the selected hostels are moderately comfortable as they fall within the standard acceptable range for indoor thermal comfort. Secondly, the PMVe – PPDe index computed for the study area imply that the thermal comfort of the hostels is between being neutral and slightly warm on the thermal sensation scale. This may be due to weather condition of the number of students in the rooms, location, architectural design, building materials used for the buildings, or internal arrangement of the rooms in the selected hostels for effective air circulation. Thirdly, there is statistical significant difference in the modified predicted mean vote – predicted percentage dissatisfied and the actual thermal sensation of the occupants in the study area.

The study has some implications for research, practice and society. For example, this study has opened up another line of research that can be followed. That is, further study can be carried out on this research work during the dry season in the south – south region in order to determine if the structures are thermally comfortable during this season. Additionally, a comparative study of Fanger's modified PMVe-PPDe and adaptive models for thermal comfort in naturally ventilated buildings can be explored.

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Reviving Master Builders
Leveraging Architect-Led Design/Build

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ABSTRACT

Why are there so few architects who build in today's era? Architect as master builder, taking on a project in its entirety - design inception, construction detailing, general contracting - seems to be a rarity in today's booming residential design and construction market. Why aren't more residential design firms leveraging the many benefits of a design-build practice? This paper attempts to outline, navigate, and demonstrate the effectiveness of the architect-led design/build delivery method. This paper does not suggest architects head over to their local hardware department and purchase a toolbelt and hammer - though points to those who do. What I would like to propose, through the following pages, is an investigation into the design-build process and how leveraging architects to lead this process can substantially influence design, construction, costs, and client's attitudes.

As architects we spend hundreds of intimate hours with our designs. We are all constantly sketching, layering trace paper, drafting, detailing, and modeling. Why not take that concentrated effort and apply it to the construction process? On paper we seem to get it, we are exceptional at visually documenting and conveying our understanding of tectonic relationships, tolerances, order of construction and the like. However, on site, contractors and builders often suggest a 'better way' to a particular assembly or detail. Why is that? Is it that architect's do not have the construction experience? Do they not have a proper understanding of real world means and methods? Do they dare to supervise? Let's dive in.

INTRODUCTION

During a typical residential project I sit down with my client to flush out their design intentions, sit hunched over at my drafting board to create a set of schematic drawings, attend multiple meetings with my client to make corrections and enhance the design, provide them with honed budgets, come back to the drafting board to create a construction set of drawings, and finally, lace up my boots and strap on my toolbelt to head out the building site to break ground and begin building. This is my new normal. I do not identify as a contractor, nor anywhere near a craftsmen, let alone a builder. I am an architect, both by education and profession. Yet, architects do not build. Or do they?

ON BUILDING

I take my technical, labor induced, construction drawings *depicting buildings* into the physical world. I advocate, as do other architects around the globe, that the role of architecture and the architect, as well as the role of construction and the builder should not be separated. In fact, these two prominent agencies are in fact the same, you cannot have one without the other. Architecture does not end, rather it has not even begun, once the design process is deemed complete. Architecture is concrete, it is the physical manifestation of the architect's drawings. The architect is the master of lead to paper. The visionary. The builder is the master of assembly. Architecture is matter, it is something you experience; touch, smell, see, and hear (Zumthor 1996). Some architects may take offense but an architect's drawings are simply representations of architecture itself, stuck on the page waiting to become a part of the physical world. Arguably, one cannot experience architecture on a page, not in two-dimensional plans, measured axonometrics, nor rendered perspective; one has to be immersed in architecture.

Without the act of construction architecture cannot transcend from the page, just as sheet music is nothing more than musical symbols until the maestro raises their baton to their orchestra to bring those symbols to life. The etymological root of the word architect is the Greek word *arkhitekton*. *Arkhi-* meaning master, or chief depending, and *tekton* meaning builder. If the Italian maestro was the master of music, then the architect of ancient times was the master of building. Yet, the contemporary architect does not build, they leave the building, the actual act of constructing and assembling, to one more qualified; the builder. But why?

When one thinks of a master builder in today's world, very few people would associate that person to be an architect. Rather, that person is often considered to be a maker, a contractor, a homebuilder, a craftsman, or in the eyes of a four-year-old a series of Lego minifigures (one such Lego master builder is named Vitruvius oddly enough). Somewhere between the ancient days of architect as master builder, the greatest discipline in the realm of building, and the architect of today, just one of many players in creating any grand edifice, the vast, and seemingly unrestricted role of the architect has shifted.

Leon Battista Alberti once defined the architect stating (Leach 1988):

> *...I should explain whom I mean by an architect; for it is no carpenter that I would have you compare to the greatest exponents of other disciplines: the carpenter is but an instrument in the hands of the architect. Him I consider the architect, who by sure and wonderful reason and method, knows both how to devise through his own mind and energy, and to realize by construction, whatever can be most beautifully fitted out for the noble needs of man…*

He continues:

> *...to do this he must have an understanding and knowledge of all the highest and most noble disciplines. This then is the architect.*

The architect was one with many talents and vast knowledge. They commanded a strong knowledge of building materials - mostly stone and wood - and their unique structural capacities. They took the helm of incredible projects of great scale; think churches/temples, aqueducts. At the same time they understood society and its needs. Creating not only structures, but forming experiences capable of impacting people at an emotional level. Why then, in contemporary times, when the design passes from the architect to the builder all too often there are instances that were not thought through or fully developed, even wrong, missing, or drawn in such a manner that the interpretation of such a drawing is left at the mercy of the builder? How can we, as architects and builders alike seek to work together to once again create and build projects soaking in quality and craft? There is a better methodology to this misguided, and often tensioned, process between the architect, the builder, but most importantly, the client. The bottom line, whether designing or building, we are doing it for our clients. If there are ways in which to streamline processes, create fewer mistakes, spend less money, and deliver an exceptional product it is advised that it be taken.

One of the benefits of having an architect lead the design-build process is their ability to leverage their design thinking; not thinking of design purely in an aesthetic approach, but rather as an actual mode of thought. An architect's education is centered around learning design thinking, they are not merely learning how to design buildings, in actuality it is quite the opposite. Architect's are learning how to think in very specific ways. This mode of thought is called design thinking, coined by Tim Brown of IDEO, it is used to leverage the process of discovery and innovation to produce better, more user specific products (Tjendra 2014). Rather than attempting to solve complex problems using pure reason and analytics, design thinking focuses on the process of discovering a plethora of solutions and applying one specific solution to the end users need; in the case of building that end user is our client. Drawing upon logic, imagination, intuition, and systematic reasoning, the mode of design thinking explores the multitude of solutions of what c*ould be*, then creates a desired outcome that benefits that particular user (Naiman). If we pivot and apply this mode of thought to a construction project, at any point throughout either process of designing or building, specific, client driven solutions can be applied, rather than specifying a solution in the manner of, "*that's how it's always done"* the end result will be a more user friendly solution while creating a more holistic project that has value for the client(s).

So what is design-build and why can it be an effective delivery method for the design and construction of projects? Design-build takes the two prominent agencies, the process of designing and the act of building, and integrates them into one entity. The design-build process can be vital for many reasons. The client only has one contractual relationship for both the design and the construction of their project, design and construction occur on the same team - whether through joint venture, partnerships, or in-house - using one unified workflow between all parties (DBIA). One business entity, one contract. This method redefines the traditional roles of the architect and the builder, while creating a consistent and informed project to the client. Projects, since they are more holistically developed, as architect and builder work together throughout the entire process, give one the sense that 'a lot of work' went into designing and constructing it. Rather than having the architect complete their drawings and handing them off for bidding - often with little control thereafter - the architect works with the builder, and vice versa, from the very first meeting with the client through the entire process. Together, the architect and the builder work on the schematic design set. The architect on the overall scheme and vision of the project, where the builder focuses their energies on their knowledge of craft and on initial pricing and budgetary concerns given the architect's scheme. If, for various reasons, schemes are deemed out of budget, architect and builder work to refine the initial design and make the necessary adjustments. On the contrary, if a budget is known initially by the client, both architect and builder work together during that design commencement phase to create a project that will adhere to the client's budgetary demands. That mode of delivery becomes far less accurate if the architect were to attempt that process on their own; they are afterall architects, not estimators.

Figure 1. Author's own image. The design-build process allows for more intimate design opportunity between the architecture, structure, and mechanical systems.

Design-build has had proven success over other, more traditional construction delivery methods, they come in less expensive, construction take less time, the overall product is delivered to the owner faster, cost growth is minimized over the other methods, and the schedule does not significantly exceed the initial trajectory (DBIA). Owners looking at those five points would have a difficult time negotiating with a builder who wants to use another method, also keeping in the back of their minds that they would still need to contract with an architect. Right from the commencement of a project clients have peace of mind knowing they are receiving a holistic project that is architecturally pleasing, all while staying within their budget and delivered on time thanks to the efforts of the design-builder. The industry has slowly caught on to this delivery method. In 2014 the American Institute of Architects released a design-build series of contracts for its members, builders, contractors, and consultants to use, and have since updated these contracts this past year, 2017 (AIA). In the traditional design-bid-build method, often times the architect, not as attuned to the construction market as the builder, is assigning rough construction costs per square foot during the schematic phase. If those numbers work for the client, they progress forward, only later to receive sticker-shock when the builder informs them their project is 20-30% greater than anticipated! At that point clients have a difficult decision to make, increase the budget or place the project on the back-burner leaving the design to sit on paper.

Figure 2. Author's own image. Architectural drawing(s) clearly did not fully coordinate with the mechanical drawing(s) to correctly or inconspicuously conceal pipe. Problem seen all too often outside of design-build delivery method.

More problems can actually arise as a design-bid-build, our traditional method, progresses forward (see Figure 2). However, bear in mind that this method still has a firm grasp on the delivery market, still considered to be the go-to contracts for owners and builders alike. Looking back to the critical aspects of any project - overall cost, speed, delivery, cost growth, and schedule growth - one would presume none of these are major factors throughout the process, when in fact, some projects can be placed on hold due to major cost overruns, schedules are prolongated thus increasing the owner's and builder's carrying costs, as well as many unforeseen alterations or changes due to a lack of coordination between the project's architect and its builder. One of the most common fallbacks to the traditional method is the coordination between the architectural drawing set and the field conditions for the project. Often in the traditional delivery the architect has little to no interaction with the builder who will be constructing the client's project, so all too often the drawings depict one instance but the built condition reflects a different condition entirely.

If we begin to assemble what we have gathered so far; the role of architects of old, architect's mode of thinking, and the efficiencies of design-build, and begin to connect all three of these into one another one would discover yet another project delivery mode, architect-led design-build. In this delivery mode, the architect acts as the design builder, they play dual roles, both as architect and as builder. This is not a new project methodology, think back to the master builders. If the ancient master builders were considered to be among the first architects, then matter of factly, they were already implementing the architect-led design-build delivery method. If architects are equipped with design thinking, mastered leadership, and have a wide knowledge of construction means & methods, tectonic assembly, and an understanding of new construction materials, then should not they be the ones by default running design-build projects? If it was not the earth and its' resources that brought man together but the architect by uniting us all under one roof, the same architect who has vast knowledge of the arts & humanities, the sciences, building technologies, construction means and methods, and the will to bring builders together to create their visions, then one would begin to advocate the architect lead the design-build project. Builders after all were just instruments to the architect, on site to assemble the architects great vision (Leach 1988). There are design-build practices across the globe blurring architecture and construction. Architects are leading projects through the lense of design-build. All the facts seem to point towards this being the next way to practice building. Clients already see the vast benefits of design-build, they would seem more intrigued to pursue the design-build option if they knew that their architect was going to take the reins. But is having the architect lead a design-build project a good idea?

ON EDUCATION

Since 2007 there has been a steady growth of licensed architects in America. Today there are around 110,000 licensed architects across the country with an additional 41,400 licensure candidates working on completing their experience hours and exams to become licensed. In fact, there are more candidates testing today than in the previous ten years (NCARB 2017). This is great news for the profession, as more people are interested in becoming licensed architects and impacting their built environment and their communities. The National Council of Architectural Registration Boards has been working hard to streamline the process to become a licensed architect, with two of the major factors being time of completion and the overlapping of education, experience, and testing. In previous years it would have taken upwards of 16 years on average, including a university education, to become licensed. NCARB reported that in 2016 the average time of completion was 12.5 years, roughly a 12% decrease on average overall (NCARB 2017). With this data one has to ask, with the reduction in overall completion time towards licensure and the overlapping of one's education, experience, and examinations, are newly licensed architects becoming younger and able to take on and lead the architect-led design-build model?

As it turns out, yes, the newly licensed architect of today is younger than ever before, but one would have to argue to prove these newly licensed architects are ready to lead design-build projects. The 2016 report from NCARB states that the average age of a newly minted licensed architect is 32 years old (NCARB 2017). At the age of 32 one has the capability to stamp drawings, thus guaranteeing the design benefits the health, safety, and welfare of our society. A decade ago the average age was around 35. A decade before that, even older. The most important factor, you must keep in mind, however, is that the average age presumes a very small overlap between one's education, one's experience, and one's examinations. If an architectural education on average takes six years, during those six years a student can be working simultaneously on their experience hours starting around year three or four; year one at some institutions. Upon graduation those same young professionals can now start their examinations, rather than waiting months or years, thus drastically reducing the timeline. To put this in perspective, I became a licensed architect at the age of 26, nine years sooner, around 20% below the national average. And there are others much younger, in 2014 Rosannah Sandoval became the American Institute of Architects youngest member at 23 (Braun 2014). Beyond these often staggering statistics of young licensed architects is the question, *what do they do for experience?*

ON EXPERIENCE

Regardless of the age of licensed architects, one should ask, in order for architect-led design-build to work, are architects actually going out there and building? Age is a significant factor in the design-build conversation because it makes one wonder, do they have the experience necessary to build? The presumption behind the question is that your typical 18 year-old student heading off to study architecture has had minimal to no actual construction experience. By the time they are graduating architecture school they are already off working in architectural firms attempting to finish their internship hours, studying & sitting for their registration exams, then finally, receiving their architectural license. It is at that point when one really has to wonder, if the average age of new architects is 32, where are these individuals gaining construction insight and hands-on experience if they have been focusing on completing their licensure process? Having practiced architect-led design-build for years I am by no means trying to be hypocritical. I must admit, that my background, before even heading off to architecture school, started in the trades. Since age 12 I have been on site working with builders, contractors, and tradesman. That experience became invaluable when I graduated high school and went off to study architecture. Architects draw from their experiences. Their personal biography is the fountain architects use to devise their architecture. Great architects acknowledge those past experiences and leverage them to make great architecture (Zumthor 1996). However, if one is not as fortunate to have the opportunities I was granted, how then do they pursue an architectural education while already having some sort of background knowledge of a facet in building? How are they gaining building knowledge? Could it be a change in educational requirements? Would the pedagogy of architectural education need to pivot to address this matter? If one does not have the experience building, becomes licensed at 25 (which could happen as the average age continues to fall closer to the age of a student graduating from university), and wants to practice design-build - can they be successful? They can create architectural drawings but are those drawings enough to leave the page?

CONCLUSION

In short, there are still a lot of questions that need to be answered before architect-led design-build truly can become a staple delivery method in the design and construction industries. Conceptually, this mode of delivering projects is an exceptional way to design and to build. To reiterate, the master builders of old, the first architects, were already implementing this method, and yet, in an era where one wants to spread out their liability as thin as possible, and limited their exposure to risk, can architect-led design-build truly be successful? There are many who advocate that it can, myself amongst them, but in order for this method to gain any sort of prominence a radical change in thinking, education, and practice would need to occur. By the time architectural graduates leave the university it is already too late in gaining construction exposure. To be successful, students wanting to study architecture need not be merely interested in the arts and humanities, but rather, gain a hands-on approach to architecture by getting involved on a construction site. By the time these students leave for university studies they already have a loose tectonic understanding, which will in turn become invaluable to them as they progress through their studies. When they reach the professional realm as architects, and once again head to the construction site, now they can begin to directly relate to what is happening on site to create the architecture. None of that is possible from behind a desk sitting at a computer drafting. To truly experience architecture you need to take the hands-on approach and truly immerse yourself in it.

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BrHEAThe System: Motivation, History, and Evaluation

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ABSTRACT

Rural Alaska faces many housing challenges, including high energy costs, poor ventilation, and inefficient buildings. The Cold Climate Housing Research Center (CCHRC) has been working to improve housing and quality of life for Alaskans and people across the circumpolar North since 1999. In an effort to address high energy costs and poor indoor air quality, CCHRC developed the BrHEAThe system, which combines space heating with heat recovery ventilation, utilizing one distribution network to deliver both fresh air and heat simultaneously throughout the home. The BrHEAThe system features an efficient oil, gas, or propane fired boiler integrated with a water-to-air heat exchanger, air filter assembly, and heat recovery ventilator (HRV) to supply healthy fresh air to occupants.

Airtight, highly insulated homes require mechanical ventilation to ensure healthy indoor air. However, bringing in fresh air during the Alaska winter can be uncomfortably cold, causing homeowners to block supply ducts, disable dampers, or turn off the ventilation completely. This leads to poor indoor air quality, and if only supply air ducts are blocked, can depressurize the house and cause dangerous backdrafting of combustion heating appliances–serious health and safety concerns for occupants. The BrHEAThe system is designed to prevent these issues by ensuring that even when the thermostat does not call for heat, the HRV continuously supplies fresh, comfortably warm air, regardless of the outdoor air temperature.

This paper will cover the motivation, development, and design features of the BrHEAThe system. It will include results on efficiency and indoor air quality from an in-progress research project and feedback from installers and homeowners who have used the system in rural Alaska.

Keywords: Heating, ventilation, HRV, integrated, comfort, indoor air quality, building science, rural and American Indian housing, whole building design approach

INTRODUCTION

Housing needs in Alaska are great. According to the 2013 Alaska Housing Assessment, the average residence in the state uses more than twice the energy annually than the average residence in a cold climate in the contiguous United States. More than 75,000 households are cost-burdened, spending more than 30% of their income on housing costs (Wiltse, Madden, Valentine, & Stevens, 2014).

As builders address high energy costs with more insulation and tighter homes, another issue has arisen: airtight homes without mechanical ventilation are at risk of moisture issues and poor indoor air quality. Researchers estimate that approximately 58% of occupied housing in Alaska fits into this category (Wiltse, Madden, Valentine, & Stevens, 2014). Unfortunately, homes with mechanical ventilation can still face indoor air quality issues. Alaska's cold winter temperatures can cause fresh air supply streams to become uncomfortably cold, even with appliances such as a heat recovery ventilator (HRV) that provide balanced mechanical ventilation to a home while transferring heat from the outgoing to incoming airstream. Cold fresh airstreams sometimes motivate home occupants, already facing high energy bills, to block or shut supply air vents, or even disable ventilation altogether. Not only does this result in poor indoor air quality, if only supply vents are blocked while air is being exhausted, this can put the house at a negative pressure relative to the outdoors, potentially backdrafting combustion heating appliances and causing serious safety concerns.

In addition to these challenges, rural Alaskans face high transportation costs and a short building season. Many communities in rural areas of the state are not on the road system, so building materials must be transported by barge or air, which both increases costs and shortens a building season that is already limited to just a few months a year.

In response to these and other housing issues, Alaska home builders and stakeholders founded the Cold Climate Housing Research Center (CCHRC) in 1999. The nonprofit organization's mission is to promote and advance the development of healthy, durable, and sustainable shelter for Alaskans and other circumpolar people. The staff, made up of designers, engineers, scientists, builders, and educators, approaches research and design projects in a collaborative fashion. In 2011, looking at the need in rural Alaska for airtight, well-insulated homes with healthy indoor air quality, CCHRC staff developed the BrHEAThe system. BrHEAThe combines heating and ventilation into one modular, simple, efficient system. The integrated system begins in the mechanical room of a small, energy efficient home, where an air-to-water heat exchanger brings space heating from a direct vent boiler to the ventilation ductwork. However, BrHEAThe's larger focus is on home safety, low energy use, and ensuring home occupants understand indoor air quality and how their house operates. BrHEAThe is an ongoing project in which designers learn from users and installers to improve each iteration of the system.

OBJECTIVE

This paper describes the motivation and history of the BrHEAThe system, as well as the methodology and preliminary results from the first formal evaluation of the system. BrHEAThe has undergone continual improvement since its inception in 2011. This paper documents

BrHEAThe's development, including the system's goals, context, and installations. Second, we describe our current analysis of the system, which consists of two parallel ongoing studies: a survey of installers and residents who have experience with the BrHEAThe system, and the monitoring of a BrHEAThe system installed in a university residence hall in Fairbanks, Alaska. The goal of this project is to establish the appropriateness of BrHEAThe for small, energy efficient homes in rural Alaska and to discern future improvements to the system.

MOTIVATION

The primary motivation behind the BrHEAThe system is to ensure good indoor air quality in small, airtight, energy efficient homes in cold climates. In order to do so, BrHEAThe ties space heating, domestic hot water, and ventilation into one modular system that is simple to install, operate, and maintain.

BrHEAThe is designed for small homes with tight envelopes and a low heat load. The air tightness of these homes means mechanical ventilation is mandatory, and BrHEAThe uses the same ductwork to distribute heat and fresh air. The combined nature of the system prevents uncomfortably cold air from coming through vents that might otherwise cause residents to shut supply ducts or turn off their ventilation.

While other combined heating and ventilation systems exist on the market, the BrHEAThe system was developed to meet unique needs of rural Alaska and one of the system's key features is its modularity. As people in rural Alaska have limited access to spare parts and specialized contractors, BrHEAThe is assembled from appliances and parts that are simple to install and easy to acquire. The modularity of the system means that the heating and ventilation appliances can be tailored to the local community. Installers and residents can choose a heating appliance and heat recovery ventilator (HRV) they are familiar with and that uses locally available parts.

Energy costs in rural Alaska are high, and CCHRC strives to make residences affordable in the long term by building homes that use as little fuel and electricity as possible. This is first addressed through energy efficient building design. However, BrHEAThe is also made up of energy efficient devices, including a heat recovery ventilator and efficient boiler. As more efficient versions of these appliances become commercially available, they can be incorporated into current and future installations of BrHEAThe. The system's flexibility can also accommodate other strategies to reduce fuel costs, including modifications such as additional vents to distribute heat from a wood stove or another back-up, low-cost heat source that may be available in a particular community.

COMBINED HEATING AND VENTILATION SYSTEMS

Combined heating and ventilation systems exist throughout the residential construction world. Many systems, like BrHEAThe, also provide domestic hot water. Current examples include HRVs combined with heat pumps or natural gas boilers (Holladay, 2015a) (Holladay, 2015b). Some HRV manufacturers provide instructions in their installation manuals on how the HRVs can be combined with forced-air heating systems. In addition to maintaining good indoor air quality by eliminating cold fresh air streams that might deter homeowners from using ventilation, combined systems can offer other advantages. Many utilize existing ventilation ductwork to satisfy low heating loads, eliminating the need for a separate space heating distribution system. Other benefits of combined systems include the potential to save space in the mechanical room, a single manufacturer's warranty, a single installation contractor, and the potential of increased efficiency compared to multiple appliances (Culp, 2002).

There has been limited testing of combined appliances. In 1998, Natural Resources Canada (NRCan) created an industry consortium to set a testing procedure and efficiency standards for prospective appliances. The consortium, known as eKOCOMFORT, set a target of an annual fuel utilization efficiency (AFUE) of 81% for the space heating component and an energy factor target of 0.75 for the water heating component. A subsequent boiler-and-HRV model demonstrated a combined annual efficiency of 83% for water and space heating using the ASHRAE 124-1991 testing standard (Culp, 2002). In Sweden, two more recent tests have focused on combined systems that meet only a portion of the space heating load with pre-heated ventilation supply air, with the intent of lowering the supply water temperature in a separate hydronic baseboard distribution systems. These studies showed that the combined appliance achieved a higher space heating efficiency as well as improving carbon dioxide levels and relative humidity (Wang, Ploskic, Song, & Holmberg, 2016) (Ploskic & Holmberg, 2013).

DEVELOPMENT OF BrHEAThe

CCHRC implemented the first BrHEAThe system in 2011. CCHRC and the community of Anaktuvuk Pass, Alaska, had previously collaborated on the design and construction of an energy efficient demonstration home shown in Figure 1. The small, airtight house, completed in 2009, featured R-60 spray foam insulation in the floor, roof, and walls. It originally relied on a qingok for ventilation, a method traditionally used in the region's subterranean homes. The qingok relied on stack effect to create a natural draft to vent air through an opening in the roof. However, this proved to be problematic in the airtight house, and adding an inline fan still didn't provide sufficient air flow. CCHRC staff worked with the homeowner to retrofit the first BrHEAThe system into the house, and it was commissioned in December 2011. The first BrHEAThe system paired a small battery-operated diesel-fired heater, manufactured for truck cabs, with an HRV. The HRV ducting served to distribute both fresh air and space heat to the living room and bedrooms. The indoor air quality of the house improved, as shown by a reduction in carbon dioxide levels by one third. However, this first system experienced a number of mechanical issues, setting off a chain of improvements for this and future BrHEAThe systems.

Figure 1: This energy efficient demonstration home in Anaktuvuk Pass,

Alaska is the location of the first installation of the BrHEAThe system.

The second iteration of BrHEAThe, shown in Figure 2, incorporated two changes. First, the battery charger for the heater was replaced with a more robust and higher capacity charging system, as the original system had failed in Anaktuvuk Pass. Second, researchers added an inline fan downstream of the HRV to prevent backpressure on the HRV supply air and boost the amount of space heating to the homes. These changes were added to the Anaktuvuk Pass BrHEAThe system and implemented in two student houses at the University of Alaska Fairbanks (UAF) in 2012.

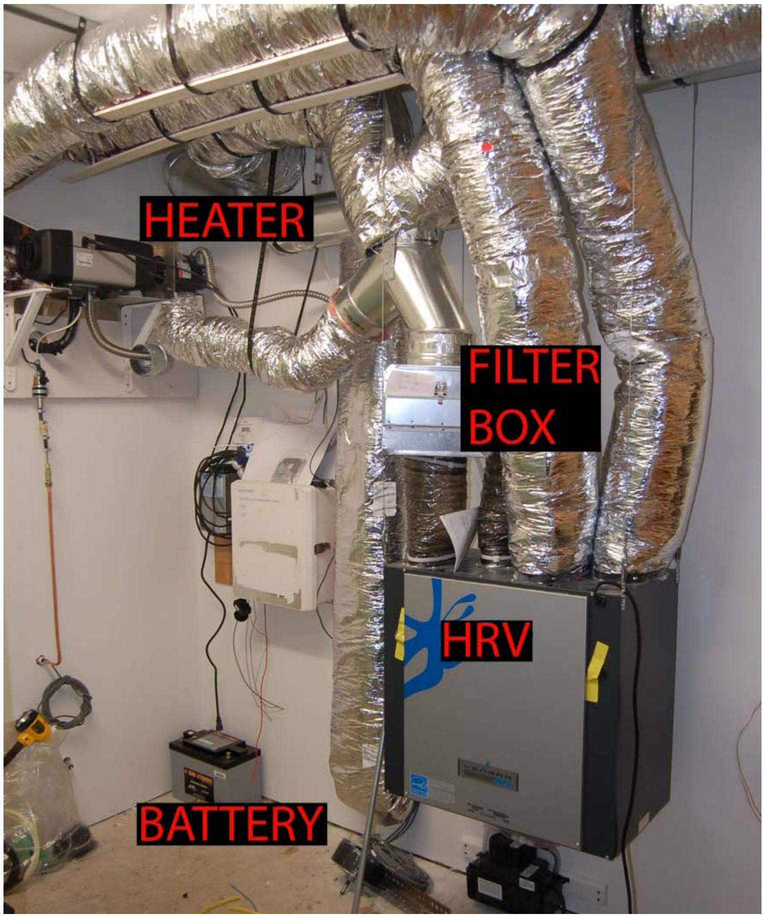

Figure 2. The 2012 BrHEAThe installation in a student dorm at the University of Alaska Fairbanks campus.

The two student homes at UAF were each 1,500 square feet with four bedrooms, a kitchen, and a living room. Similar to the Anaktuvuk Pass home, they are well-insulated and airtight. BrHEAThe, featuring the diesel-fired heater, an HRV, and the inline booster fan, provided space heating and ventilation. However, the system continued to experience occasional problems. First, the truck cab heaters were not meant for continuous operation and needed several repairs over the first two years. Second, some residents experienced overheating in their bedrooms, causing them to shut supply vents and prevent fresh air from entering the rooms.

Researchers monitored the indoor air quality of the student homes for two weeks in the winter of 2012 and found that the BrHEAThe system in both houses failed to meet the ASHRAE Standard 62.2 recommended ventilation rate (results are reported in Kotol, 2013). However, in both cases this was due to students setting their HRV on the minimum setting meant for low occupancy. This resulted in carbon dioxide levels in the homes exceeding the ASHRAE 62.1 recommended value of 700 parts per million over ambient 40% of the time in one house and 60% percent of the time in the other. The study also found that the two homes with BrHEAThe systems experienced larger temperature swings than two similar houses that had radiant floor hydronic distribution for space heating. In one of the BrHEAThe homes, bedroom temperatures reached and exceeded 80°F, confirming the overheating that had previously been reported by occupants (Kotol, 2013).

After two years of operation, both systems were replaced. In one home, a commercially-available heating and ventilation combined appliance was installed. This system is still operating today, but is oversized for the heat load of the home. In the second home, an oil-fired boiler replaced the truck cab heater. The boiler also now provides domestic hot water to the home. Researchers designed a water-to-air heat exchanger box (Figure 3) to place heat from the boiler into the HRV supply stream. The box also contains room for additional air filters and a relief port to add supply air when the downstream fan comes on.

Figure 3. The water-to-air heat exchanger box contains room for additional air filters. It is currently manufactured by a local company.

Several homes in Alaska use the current version of BrHEAThe, including single-family residences in Buckland, Galena, Point Lay, Brevig Mission, and Minto and duplexes in Bethel and Tanana (see Figure 4). Each installation has some variation from the others, as communities and contractors are able to choose an HRV and boiler with locally available parts.

Figure 4. Past and current locations of BrHEAThe installations in Alaska.

Each BrHEAThe residence has an energy efficient, airtight building envelope and a small home footprint. This allows the BrHEAThe system to provide comfortable heat and adequate fresh air to each area of the home without requiring zoning. BrHEAThe projects incorporate extensive homeowner education about the BrHEAThe system itself, home design, and the need for mechanical ventilation to ensure healthy indoor air quality. Where possible, BrHEAThe installers commission the systems and perform a system walk-through with the homeowner. General contractors and designers also learn about BrHEAThe so they can explain the system to their crew and future residents. There is currently a homeowner manual and video on the system to explain the purpose behind BrHEAThe, operational features, and maintenance requirements.

CURRENT DESIGN

The current BrHEAThe system ties space heating, mechanical ventilation, and domestic hot water into one system. At the center of the system is an energy efficient direct vent combustion boiler, which provides heat to two zones–the domestic hot water tank and space heating (see Figure 5).

The HRV provides continuous mechanical ventilation throughout the home. The supply air passes through the water-to-air heat exchanger. When there is no call for space heat, the supply air passes through this assembly and into the distribution ducting with no change in temperature. A control system can trigger space heating to be added to the fresh air stream in two instances. First, the boiler will turn on when there is a call for heat from a centrally located thermostat. In this case, the inline booster fan located downstream of the heat exchanger also comes on to increase the volume of heated air that is provided to rooms. The heat exchanger box contains a relief air port to provide the extra air volume to the HRV supply stream.

The control system also contains a temperature sensor in the supply airstream to the house. This temperature sensor triggers the boiler to turn on when the fresh air supply becomes colder than comfortable. To prevent residents from cold drafts, the boiler provides a smaller amount of heat to the airstream to keep the fresh air temperature at a minimum of 60°F. In this case, no extra air volume is necessary, and the downstream fan remains off.

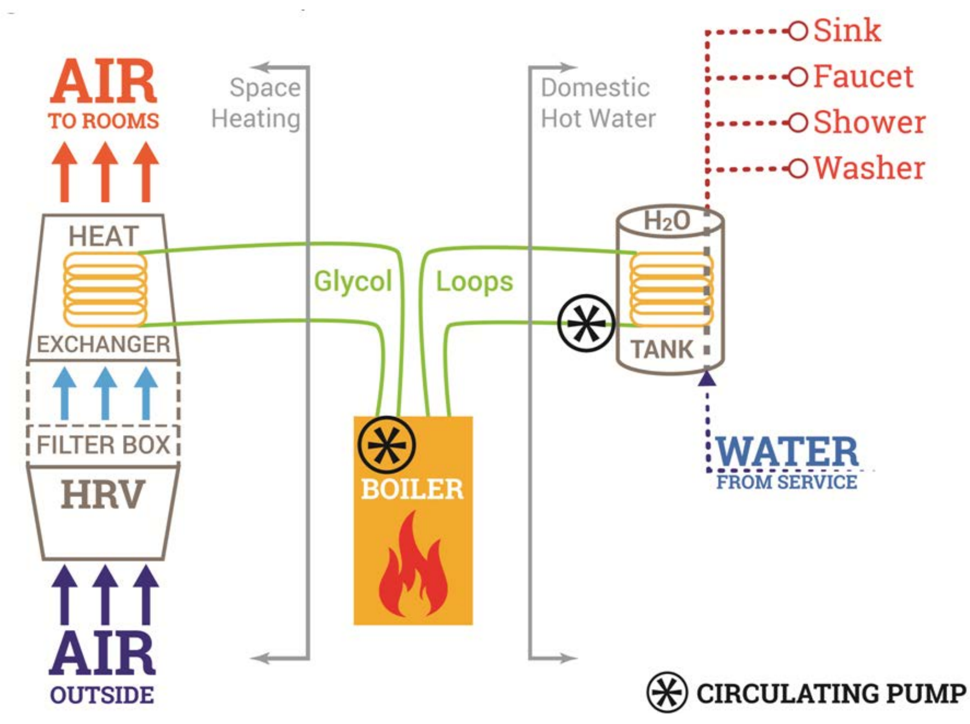

Figure 5. A diagram of the BrHEAThe system shows its main components, including a boiler, HRV, and heat exchangers. A booster fan (not shown) located downstream of the filter box and heat exchanger helps supplement the air stream to rooms when the house thermostat calls for heat.

Each home has one thermostat servicing a single space heating zone. BrHEAThe is meant to be installed in small, energy efficient homes where multiple zones are not necessary. However, air movement between rooms is facilitated through acoustical vents located above bedroom doors that help prevent rooms from becoming uncomfortably cold or hot. In homes with a secondary heating appliance, such as a wood stove, the vents also help distribute the additional heat.

The heat exchanger assembly contains an extension to provide extra filtration to the supply air to the house. Many communities in Alaska experience poor outdoor air quality due to smoke from wildfires and road dust in the summer and particulates from wood-burning appliances in the winter. The option to add additional filters to the supply air stream helps families using the BrHEAThe system ensure their indoor air quality remains healthy at all times.

The BrHEAThe system is modular and can accommodate various models of HRVs, boilers, and water tanks. This allows the appliances to be tailored to the home, with components that local installers and residents are familiar with. It also allows appliances to be updated to more energy efficient versions as they become commercially available.

INSTALLER AND RESIDENT FEEDBACK

With each BrHEAThe installation, CCHRC has sought informal feedback from installers, general contractors, funders, and home occupants on how the system can be improved. In this project, researchers are conducting a formal survey of people with past experience with the BrHEAThe system. The purpose of this end user survey is to formally document experiences with BrHEAThe and to evaluate the general performance of installed BrHEAThe systems.

Staff will use the following questions to guide the interviews and establish advantages and disadvantages of BrHEAThe. Designers will use this information to inform future improvements to the system.

1. Are homeowners satisfied with the performance of their BrHEAThe system? Is the system able to maintain a comfortable air temperature and adequate indoor air quality? What are the operation and maintenance requirements of the system? Does energy use match homeowners’ expectations?
2. Are installers satisfied with the installation and commissioning process for the system? Is the process easy to complete? Are parts readily available? Is the system appropriate for the house it is installed in?
3. How can BrHEAThe be improved in the future? Are there ways to improve the mechanical components and design, the controls, or the education component?

IN-SITU MONITORING

Researchers will monitor one BrHEAThe system during the winter of 2017-2018 to formally evaluate the current design and discern potential improvements for future versions. This test will occur at the UAF student dorm in Fairbanks, Alaska, known as the Birch house (shown in Figure 6). Four students will live in the home from late August 2017 through May 2018, with a one-month break over the winter holidays. The study aims to answer the following research questions:

1. Does the current version of BrHEAThe maintain the indoor air quality of the Birch home to acceptable standards?
2. What is the seasonal energy use of the BrHEAThe system in providing space heating and domestic hot water? How does this compare to the AkWarm energy rating software prediction for fuel use?
3. What effect does the distribution system of BrHEAThe (using a heat exchanger and inline booster fan to distribute space heat via the ventilation duct system) have on the overall mechanical system of the home?
    a. How does the seasonal energy use of the inline booster fan compare to the radiant floor distribution pump in a neighboring house with a similar footprint and oil-fired boiler?
    b. Are there safety or comfort concerns resulting from potentially high supply air temperatures?
    c. Does the inline booster fan cause the intake and exhaust streams of the HRV in normal operation to become out of balance?
    d. Should an intake or exhaust stream of the HRV become blocked, as in the case of a dysfunctional damper, what effect does the inline booster fan turning on have on the pressurization of the house?

The first of these questions will establish if the BrHEAThe system can meet its main objective of ensuring adequate indoor air quality, which will be measured by three markers of temperature, relative humidity, and carbon dioxide concentration. Sensors will be located in six locations in the home–the downstairs hallway, upstairs kitchen and living area, and each of the four bedrooms. Researchers will also measure the carbon dioxide concentration of the exhaust stream of the HRV. As Fairbanks is in a cold climate zone where winter temperatures can fall to -50°F, the HRV employs two frost protection strategies to prevent the core from freezing: first, initiating an 800-Watt electric heater in the supply stream and second; dampening the supply air stream. There is concern that during prolonged cold periods, dampening the supply air could result in inadequate fresh air being supplied to the home to maintain acceptable indoor air quality.

Figure 6. The Birch house at the University of Alaska Fairbanks houses four students each year.

The second question will address if the system is appropriate for the energy efficient house it is installed in. BrHEAThe systems are meant for small, airtight homes and the intent is to stay true to the overall goal of low annual fuel use, especially in communities with high energy costs. Thus, the system should be able to provide adequate space heat and domestic hot water in the range predicted by the energy rating software used in Alaska, known as AkWarm.

Finally, the third question addresses the safety, occupant comfort level, and energy use of the current control scheme and distribution strategy of BrHEAThe. The designers of BrHEAThe are continuing to improve this portion of the combined heating and ventilation system and strive to find a balance between simplicity, occupant safety, occupant comfort, and energy use. This monitoring study aims to identify any issues with the current design so future versions of the system can incorporate potential solutions.

PRELIMINARY RESULTS

As of August 2017, researchers have interviewed eight individuals with BrHEAThe system experience, including one home occupant, three installers, one manufacturer, and three people who have designed homes to use BrHEAThe. Additionally, researchers performed house pressurization testing to determine the effect of BrHEAThe's inline booster fan on the house pressure relative to the outdoors in different scenarios. Further interviewers will occur after the 2017 building season, and in-situ monitoring will begin in September after the test house is occupied for the 2017-2018 school year.

Homeowner satisfaction Thus far, the only home occupant interviewee reported general satisfaction with the BrHEAThe system. The interviewee was a resident in the student dorm at

UAF during a school year when the BrHEAThe system used the truck cab heater. He remembered the system working well, except for two issues. First, he remembered it breaking down and needing repair. Second, he reported that during cold days in the winter, the BrHEAThe system had trouble keeping both floors of the home up to the thermostat setting. Downstairs was comfortable, where the thermostat was located, but the upstairs was cool enough to lead students to turn on electric resistance space heaters.

Installer satisfaction In general, installers and designers have found no particular issues with BrHEAThe installations. No installation or design issues were reported, and all parts were found to be readily available. The majority of installers commented that the main advantage of BrHEAThe is that it ensures ventilation in small, airtight homes. In rural homes with high occupancy, BrHEAThe's guarantee to provide fresh air is necessary for occupant and building health, and BrHEAThe puts fresh air at the forefront. The system also helps fight the stigma that is found among some Alaska residents that mechanical ventilation uses a lot of extra electricity to bring in cold air. A second advantage, mentioned by three interviewees, is the system's flexibility in accommodating a variety of HRVs and boilers. This allows builders to ask residents what appliance they prefer, so that BrHEAThe does not introduce too many new variables to the construction process in local communities.

One potential disadvantage of BrHEAThe is its dependence on the building's design. The system requires a home that is small and efficient to be able to provide adequate heat. It is best when the building is designed with BrHEAThe already in mind, so there is room to place the ducting and the system components in the mechanical room are readily accessible to the homeowner for maintenance such as cleaning HRV filters. Installers also noted that the heat exchanger, a necessary component of the system, is expensive, and can take time to manufacture and ship, as it is custom-made to order.

Potential improvements Interviewees had several suggestions for future improvements. First, two individuals pointed out that BrHEAThe's one size heat exchanger means that to a large extent, the house must fit to the system, rather than the traditional method of sizing a heating appliance to the residence's heat load. Suggestions to accommodate larger house footprints included adding in an option for a larger inline booster fan and ductwork, and adding zoning. Interviewees also provided other potential improvements concerning the heat exchanger, such as to search for one available off-the-shelf, and to continue to make sure that it can adapt to different heating appliances and HRVs so the system's modularity can be maintained.

Two interviewees provided suggestions to improve heat distribution and system efficiency by adding downstream temperature and airflow monitoring to regulate temperature and ensure enough airflow to each room. If supply air is too hot, the boiler temperature could be brought down as needed. Another suggestion was to re-program the controls so that warm water flows through the heat exchanger more often, as opposed to hot water less often.

Finally, interviewees suggested improving the education component by focusing more on installers and future community members or housing authority employees that may need to maintain or repair systems. A video or manual that explains both the "how" of the installation process, in addition to why each step is performed would give people working on the systems clear procedures and the reasons behind them.

Performance Ideally, houses should be at near neutral pressure in reference to the outdoor air. If the house is at a positive pressure relative to outside, this puts the envelope at risk of moisture intrusion as warm, moist interior air seeks pathways to the outside. This can lead to mold and other moisture-related issues in wall and roof assemblies. On the other hand, if the house is at negative pressure relative to outside, combustion appliances can backdraft, introducing dangerous gases into the home. Balanced mechanical systems such as HRVs are designed to introduce the same amount of air as they exhaust, to keep homes at neutral pressure. BrHEAThe adds a heat exchanger and an inline booster fan to the supply stream of an HRV in order to meet space heating loads. This fan comes on when the thermostat calls for space heat. Researchers tested the effect of this fan on the house pressurization and supply and exhaust air streams of the HRV to discover if the fan placed a home at greater risk for either positive or negative pressure.

The testing occurred in the Birch home at the University of Alaska Fairbanks. The air leakage rate of the house, measured with a blower door, is 1.33 ACH50. In this home, the balanced HRV introduces and exhausts 84 cubic feet per minute (cfm) when on fan speed level 2, the level meant for typical occupancy (level 3 is a boost mode, and level 1 is for low occupancy). With the inline booster fan activated, the supply air stream increases to 96 cfm. The heat exchanger box contains a relief air port which opens when the fan turns on, and the majority of extra air enters the supply stream through this port. However, the fan also draws more air through the supply of the HRV, putting the house at positive pressure, which is somewhat mitigated in that this pressure also causes the HRV to exhaust more air as well. The exhaust air flow increased to 91 cfm. As seen in Table 1, the resulting house pressure is 3.9 Pascals (Pa) with reference to outside, 3 Pa more than measured with the fan off.

Further tests, summarized in Table 1, documented the effect of the inline booster fan on house pressure if a supply or exhaust stream of the HRV becomes blocked. Many HRV models use dampers in recirculation mode. These dampers shut off supply and exhaust streams in cold temperatures to prevent the core from freezing, and reopen after a set period of time of re-warming the core with interior air. However, if the supply damper fails to re-open it puts the house at risk of negative pressure and if the exhaust damper fails to re-open it puts the house at risk of positive pressure. In the Birch house, blocking the supply stream put the home at a negative pressure of 4 Pa relative to outside, which was slightly reduced with the inline booster fan on. While the fan drew air from the relief port of the heat exchanger box, it slightly reduced air flow leaving the house. On the other hand, the inline booster fan turning on made the house pressurization much worse with the exhaust stream blocked, nearly doubling the pressure relative to outside as it drew in more air from the HRV supply. This positive pressure puts the house at greater risk for moisture intrusion and indicates that installers should consider HRVs for BrHEAThe that do not pose a risk of dampers failing to re-open. In fact, the HRV in the Birch house does not have a recirculation mode, instead relying on an electric pre-heater and a damping down of a supply-side fan in cold temperatures without closing off any ducts.

Table 1. Results of house pressurization testing with inline booster fan on and off.

Test	House pressure relative to outdoors
Control – HRV on level 2	House at 0.9 Pa to outside (positive pressure)
HRV on level 2, inline booster fan on	House at 3.9 Pa to outside (positive pressure)
HRV on level 2 with supply stream blocked, inline booster fan off	House at -4 Pa to outside (negative pressure)
HRV on level 2 with supply stream blocked, inline booster fan on	House at -3.8 Pa to outside (negative pressure)
HRV on level 2 with exhaust stream blocked, inline booster fan off	House at 5.7 Pa to outside (positive pressure)
HRV on level 2 with exhaust stream blocked, inline booster fan on	House at 11 Pa to outside (positive pressure)

FUTURE

In 2017, BrHEAThe continues to evolve with each new installation. This year, one BrHEAThe system was installed in a duplex in the village of Tanana, Alaska, and another installation is scheduled for early fall in a single family residence in Oscarville, Alaska. While these installations remain true to the combined, modular nature of the BrHEAThe system, they have many differences from the first 2011 system. Both 2017 installations feature the current design with a hot water boiler, air filter, booster fan, and water-to-air heat exchanger box instead of the original battery-operated diesel-fueled truck cab heater.

Future installations will continue to improve to make them simpler, lower cost, and more energy efficient. Two potential changes are currently under consideration. First, CCHRC is searching for a manufacturer to make the water-to-air heat exchanger and air filter assembly at a lower cost than it is presently available. At this time, the box is custom-made to order by an Alaskan manufacturer, which drives the cost of the BrHEAThe assembly up and also makes each installation dependent on a single manufacturer. Second, as the availability of cold climate air source heat pumps (ASHPs) is increasing in Alaska, BrHEAThe designers are looking to potentially incorporate an ASHP into the assembly to replace the hot water boiler at times when it would result in energy savings.

This project will also inform changes to BrHEAThe. The indoor air quality monitoring, seasonal fuel use, and safety tests will identify the strengths and weaknesses of the system, pointing researchers to areas that need improvement. Furthermore, the interviews with past users should identify both design changes and indicate how well the education component of the system is communicating BrHEAThe's purpose to installers and residents.

CCHRC welcomes feedback and upgrades to BrHEAThe. At the same time, system designers are constantly aware of preserving the system's original intent. Each new version must first meet the primary goal of ensuring healthy indoor air for Alaska homeowners with an energy efficient, simple system. In doing so, BrHEAThe is one part of the solution to meeting the challenges to housing in Alaska.

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Computer Modeling of Masonry Structures

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ABSTRACT

In earthquake analysis of structures seismic forces caused by the ground accelerations acting on brick or concrete block masonry structures along with gravity loads have no classical computer software available for designers to use. How to model masonry structures with uniform vertical and horizontal reinforcement distribution can be a problem especially for young engineers. Buildings with bearing walls with vertical and horizontal tie beams are common for short buildings and have no computer software support as well. During the past 20 years with considering different models for masonry structures using existing common software for structural frame and shear wall analysis, different models were developed. These models consist of hard and easy models. Some of them have huge input and output files along with hard process for determining the internal forces and some with small input and output files and easier process to find the internal forces.

In this paper besides introducing different computer modelling for masonry structures under gravity and lateral loading, different examples will be presented and the results will be compared.

INTRODUCTION

Most of the building collapses and human fatalities caused by earthquake were in non-industrial countries. Buildings with non-reinforced concrete masonry blocks or bricks will be damaged or collapsed during even moderate earthquakes. In recent years governments paid more attention to the importance of reinforcing these kind of structures. Lack of modelling made these kinds of efforts harder, and engineers have no tool to analysis masonry structures. There are some recommendations in different codes for just how to reinforce masonry structures with no approved method of analysis to find internal masonry element forces. Two different common reinforcing might be considered for masonry bearing walls, a) uniform distribution of horizontal and vertical reinforcement, and b) concentrated vertical and horizontal bars inside concrete ties.

MASONRY SHEARWALLS

Walls

In masonry structures most of the walls are carrying gravity and lateral loads. These walls might be solid or with doors or windows openings. Two types of flexural rupture might be occurred for the walls are a) In plane bending, and b) out of plane bending.

In and Out of Plane Bending

Masonry shear walls would be under in plane bending if bending axis is perpendicular to the wall plane. Masonry shear walls with low amount of vertical reinforcement and high H/L (height to length) ratio might experience flexural rupture. Out of plane masonry shear walls (bending axis is at the wall plane) behavior would be the same as reinforced concrete beams.

Shear Failure

Masonry shear walls with or without opening under shear force might experience shear failure during an earthquake that are shown in Figure 1. Reducing the height to length of the wall ratio will increase the risk of the shear failure of the wall. Increasing vertical rebar in the wall (that is mostly carrying the wall moment) along with reducing horizontal rebar might introduce shear failure to the wall. Laboratory results have shown that shear strength of a masonry shear wall under cyclic shear with 1 to 5 cycles per second will be increased. For example the shear strength of a masonry shear wall under 5 cycle/sec shear force increased about 15% relative to static shear load. Another test showed that dynamic cyclic load will decrease stiffness and shear capacity of the wall even if the wall has flexural behavior.

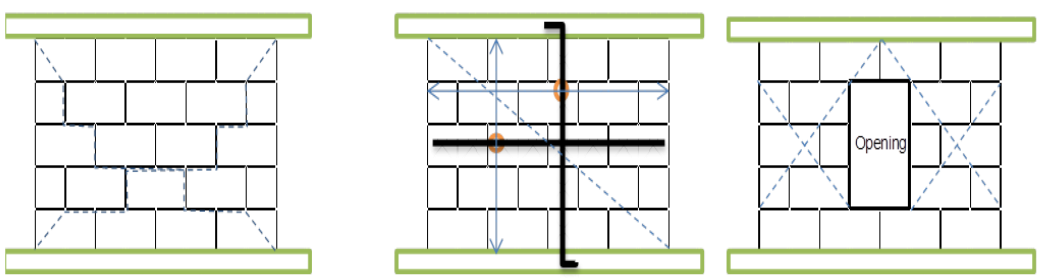

Figure 1. Shear failure in non-reinforced and reinforced masonry shear walls

TENSION, SHEAR, AND COMPRESSION STRENGHT

Mortar Strength

The most common mortar is cement mortar with different cement/sand ratio. Table 1 shows different mortar strengths.

Table 1. Mortar tension, compression, and modules of elasticity strength

Modules of Elasticity				Compression Strength		Tension Strength		Mortar type (Cement/Sand)
Dynamic		Static						
Kg/cm2	psi	Kg/cm2	psi	Kg/cm2	psi	Kg/cm2	psi	
23200	329980	16100	228990	94.1	1338	7.1	100	1/3
16800	238950	11900	169260	61.1	869	2.5	35	1/6
14800	210500	7700	109520	53.7	764	0.2	2.8	1/12
4900	69690	4200	59738	47.5	675	0.3	4.3	Mud

Table 2 shows different unit (brick, block along with mortar) strengths.

Table 2. Masonry unit strength

Brick, concrete block Compression strength								Mortar (Cement/Sand)
140Kg/cm2	1990psi	105Kg/cm2	1493psi	70Kg/cm2	995psi	35Kg/cm2	497psi	
10	142	8.5	120	5.5	78	3.5	50	1/6
12.5	177	10.5	149	7	100	3.5	50	1/3

Mortar and masonry damping ratio

Table 3 shows cement mortar damping ratios with different cement/sand ratios.

Table 3. Mortar damping ratio

Mortar type (cement/sand)	Damping Ratio
1/3	1.8 to 5.5
1/6	2.2 to 6.2
1/12	3.8 to 7.5

Masonry buildings' damping ratio is between 3 to 20 percent.

MODELLING OF MASONRY STRUCTURES

In order to determine internal forces of masonry structures with brick or masonry block and tie elements different models will be considered as follows:

1- Truss modelling of walls and ties,
2- Frame filled with masonry wall modelling,
3- Strong beams and column modelling,
4- Strong beam and column modelling along with tie (boundary) elements,
5- Shell modelling of masonry walls,
6- Asolid modelling of masonry walls,
7- Etabs modelling of masonry walls.

In order to determine and compare internal forces based on above mentioned models, a small residential masonry building with 20x20cm horizontal and vertical ties and 20cm thick masonry walls will be analysed. Shell, Asolid and Etabs models are more suitable for masonry structures that have no horizontal and vertical ties and instead rebar reinforcement are distributed uniformly along the height and length of the wall respectively. Gravity load will be carried by masonry walls and finding internal forces caused by gravity loads would be easy. In this example just the elements' internal forces caused by lateral loading will be calculated. Figure 2 shows the residential example building.

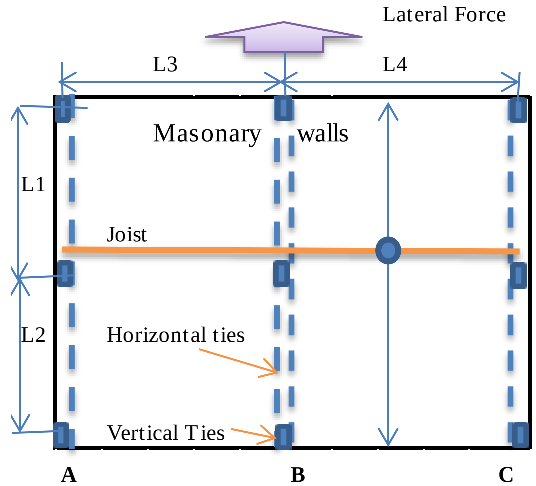

Figure 2. One story residential masonry structure (Plan view)

For this example assumptions are made as follows:
Thickness of the wall t=20cm
L1=L2= 390cm
L3=L4= 520cm
Ec= 2x10^5 Kg/cm2 for concrete ties
Ew= 7x10^4 Kg/cm2 for masonry wall
Height of the structure h= 300cm
Lateral load= 15600Kg

Truss modelling of walls and ties

This model is suitable for brick and block wall building structures that horizontal and vertical ties are used. In this example just walls with no opening will be considered.
Figure 3 shows masonry wall with horizontal and vertical ties.

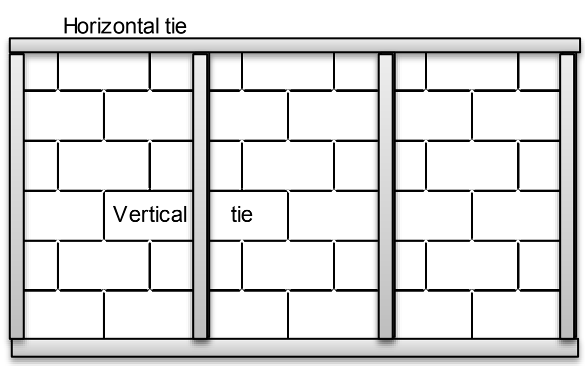

Figure 3. Brick wall with ties

Horizontal and vertical ties will be considered as horizontal and vertical truss elements and masonry wall will be considered as diagonal elements of the truss as shown in Figure 4.

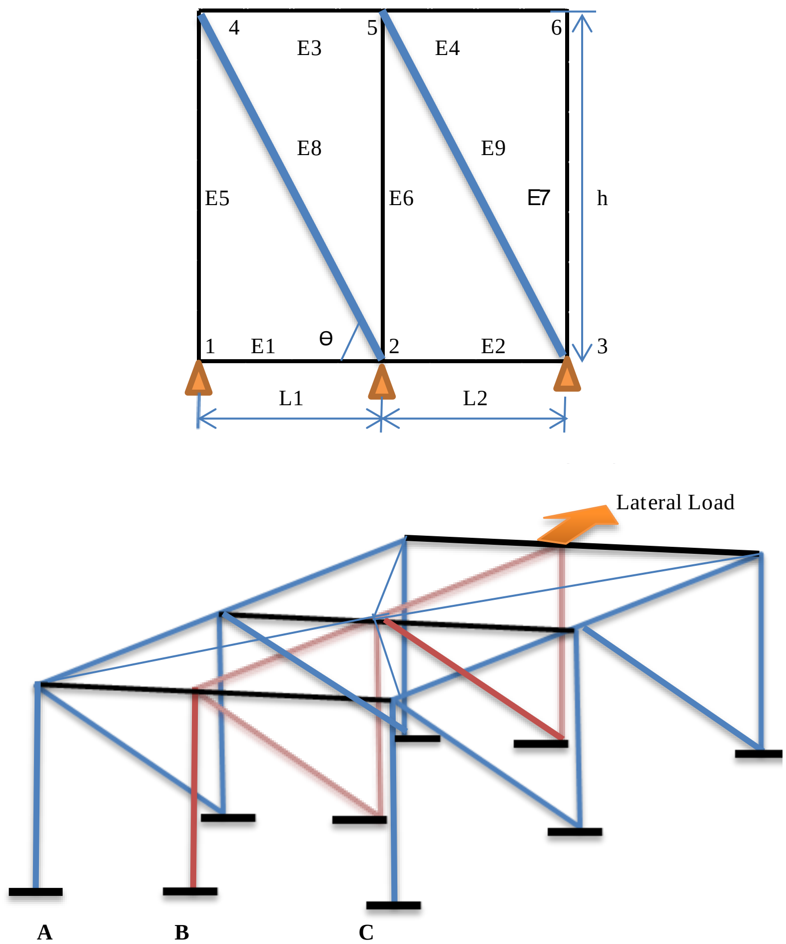

Figure 4. Truss modelling (2D and 3D)

All horizontal and vertical elements are 20x20cm with Ec=2x10^5 Kg/cm2. Diagonal elements width would be $(\sqrt{(390+20/2)^2+300^2})/10 = 50\text{cm}$ and its thickness is equal to 20cm. Center to center of vertical ties plus half of the tie's width is considered for as the diagonal element width. Modulus of elasticity for these elements is considered
Ew= 7x10^4 Kg/cm2.
After computer analysis we can find all truss elements' internal forces, and the diagonal internal forces will provide the masonry shear forces. Final results for this model are shown in Table 4.

Frame filled with masonry wall

This model is suitable for brick and masonry wall building structures that horizontal and vertical reinforcement are used concentrically as horizontal and vertical ties. In this example just walls with no opening will be considered. Figure 5 shows masonry wall with horizontal and vertical ties along with compression, tension and shear cracks caused by lateral load.

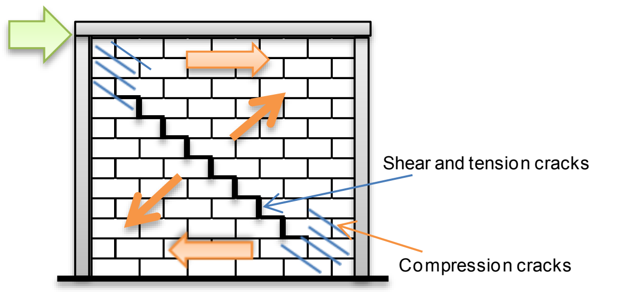

Figure 5. Frame filled with masonry wall

Figure 6 shows stresses and internal forces that will be considered based on this model.

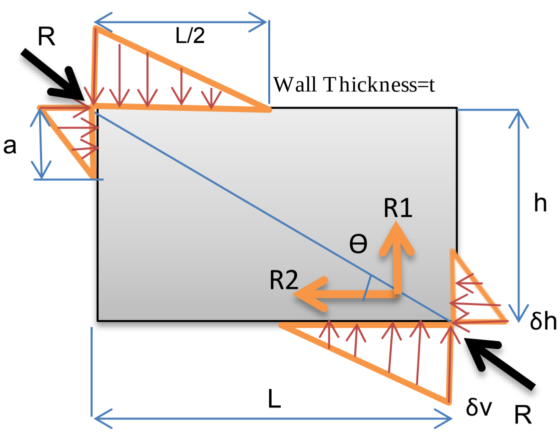

Figure 6. Internal forces in frame filled with masonry wall

The following equations will provide internal forces for this model. In this model we should calculate the diagonal force (masonry internal force), and in this paper the diagonal force (R) is calculated from truss model analysis and it is R=3280Kg. In this example L=L1=L2=390cm

$$\lambda = \sqrt[4]{Ew.t.\frac{Sin(2\theta)}{4I.h.Ec}} \tag{1}$$

In which
Θ=Atan(h/L) = 37.57^o
I = Moment of inertia of the vertical 20x20 tie = (20^4/12)
Then the contact length between the vertical tie and the masonry wall will be calculated from following equation.

$$a = \pi/(2\lambda) \tag{2}$$

The horizontal and vertical stresses will be obtained from solving following equations.

$$(\delta v \frac{L}{4})^2 + (\delta h\, a. \frac{t}{2})^2 = R^2 \tag{3}$$

$$\delta v. L^2 - 2ah. \delta h = 0 \tag{4}$$

Then the masonry wall shear force R2 will be calculated from following equation.

$$\mathrm{R2} = \mathrm{a.t.\delta h}\ /2 \tag{5}$$

Results of this model are shown in Table 4.

Strong beam and column model

In this model the whole wall including ties and masonry will be consider as a frame with strong beam and column.

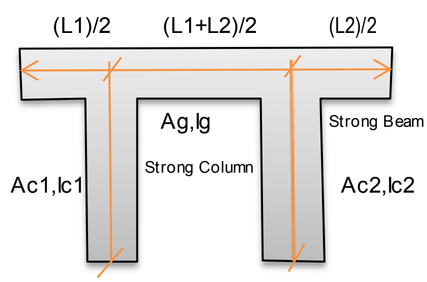

Figure 7. Strong beam and column model

Beam and column Physical quantities that are shown on Figure 7 can be calculated as follows.
Cross section of the first column Ac1 = t.L1
Cross section of the second column Ac2 = t.L2
Cross section of the beam Ab = t.h/2
Moment inertia of the first column Ic1 = t.$(L1)^3$/12
Moment inertia of the second column Ic2 = t.$(L2)^3$/12
Moment inertia of the first column Ib = t.$(h)^3$/96

A 3D model that is shown in Figure 8 is created and analysed by using above mentioned physical quantities. Results are shown in Table 4.

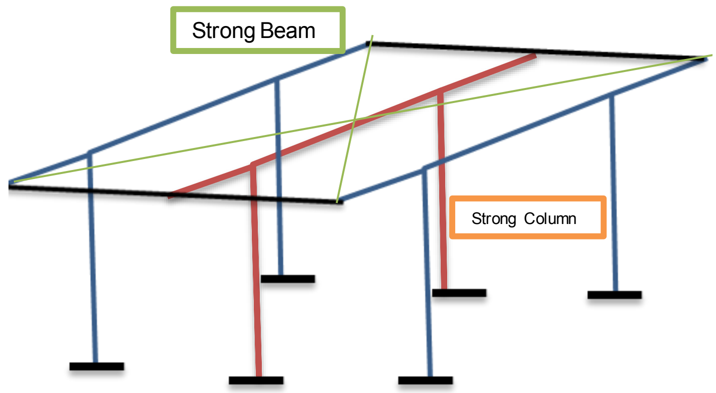

Figure 8. Strong beam and column 3D model

In this model all the columns and beams are 400x20cm and 150x20cm respectively with modulus of elasticity Ew for these members. All the beams perpendicular to the strong beams are 20x20 with modulus of elasticity Ec. In order to determine the vertical ties' axial forces caused by lateral load, a combination of axial force caused by strong column's moment and axial force is used. Consider M and F are the strong column's moment and axial load respectively, and then the vertical tie's axial load would be:

$$P1 = (\pm)M1/L1 + F1/2 \quad (6)$$
$$P2 = (\pm)M2/L2 + F2/2 \quad (7)$$

M1 and F1 are the first strong column internal forces and M2 and F2 for are the second strong column moment and axial force. So one side of the strong column would be under compression caused by moment with (+) sign and for other side of that strong column tension will act on the vertical tie with (-) sign. For the interior vertical tie that is clear that both axial forces must be added together. The results of this model are shown in Table 4.

Strong beam and column along with boundary model

In this model just masonry portion will be consider as strong column along with tie columns as boundary elements. Strong beams are the same as before. Figure 9 shows 2D and 3D of this model.

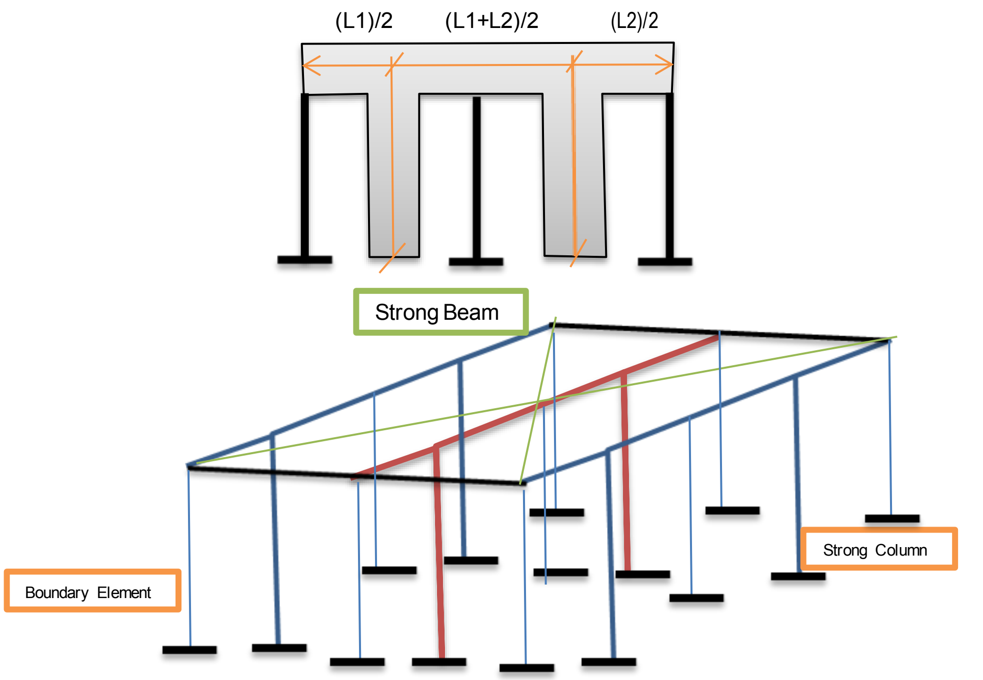

Figure 9. Strong beam and column 3D model with boundary elements

In this model all the strong columns are 370x20cm with modulus of elasticity Ew and the boundary elements are 20x20cm with modulus of elasticity Ec and strong beams are 150x20 with Ew. After analysing the 3D model with computer programs the vertical tie internal forces would be part of the output and the strong column effect must be added to that result. If internal axial force for the exterior vertical boundary element is F then the final axial force for exterior tie would be:

$$\mathrm{P1} = \mathrm{F1} + (\pm)\mathrm{M1}/(\mathrm{L1} - 20) \tag{8}$$

The interior boundary element axial force can be calculated as follows. A 20cm is deducted from L1 to find the width of the masonry only.

$$P2 = F2 + \frac{(\pm)M1}{L1-20} + (\pm)M2/(L2 - 20) \tag{9}$$

Final results are presented in Table 4.

Shell, Asolid, and Etabs models

These models are popular and in this paper instead of modelling the whole building just one of the three walls modelled and results are presented in Table 4. It is notable that one third of the lateral load is considered for one wall due to three equal wall's stiffness.

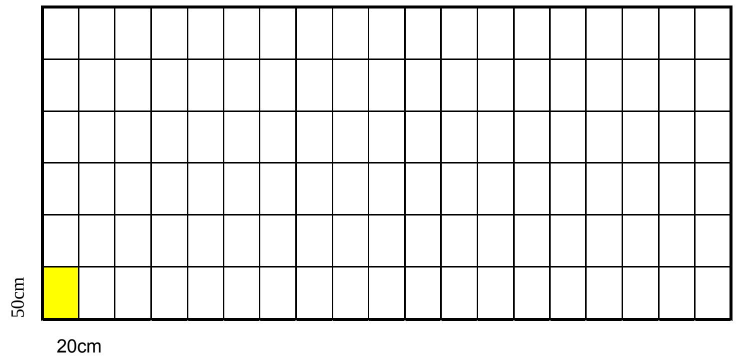

Fig. 10 Shell, Asolid, and Etabs 2D model

In order to calculate the internal forces for vertical ties, 50x20cm elements are considered for these models as it is shown in Figure 10. These models have big files with huge amount of out puts that make it harder to find the element's internal forces.

RESULTS

After analysing all seven models and calculating the vertical tie axial forces and masonry wall shear forces, the results can be found in Table 4.

Table 4. Wall element's internal forces

Model	Exterior tie axial Force (Kg)	Masonry Wall Shear Force (Kg)
Truss	2000	2599
Frame filled with wall	2000	2599
Strong beam and column	1996	2600
Strong beam, column and boundary elements	2050	2590
Shell	2470	3320
Asolid	2420	2570
Etabs	2000	2590

CONCLUSIONS

Based on the input and output files and final results that are presented in Table 4. the following conclusions have been made:

1- The easiest model that can be used for analysing masonry structures is truss model and the results are the same as Etabs model with good confidence that forces are accurate and reliable.
2- Shell, and Asolid models have very big input files, and will create huge output files that processing those data to find the internal forces will take long time. Static joint force disequilibrium is another problem that these models still have. Masonry elements cannot carry tension, and if masonry is under tension we should remove those elements to get accurate answer. So these models are not easy to use.

3- Etabs model needs to remove the masonry elements that are in tension to determine correct elements' internal forces.
4- Strong beams and columns with or without boundary elements is the third easiest model after truss and Etabs models, and will provide good results.

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